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The Efficiency of Soil and Fertilizer Phosphorus as Affected by Soil Reaction

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THE EFFICIENCY OF SOIL AND FERTILIZER PHOSPHORUS AS AFFECTED BY SOIL REACTION

ROBT. M. SALTER AND E. E. BARNES

Phosphates rank first in importance among fertilizer materials applied to Ohio soils. The factors affecting their need and their comparative efficiencies are thus of considerable practical importance. For many years farmers have been interested in the value of superphosphates as against bone meal, basic slag, and raw rock phosphate. In recent years treble superphosphates and still more recently the ammonium phosphates and ammoniated superphosphates have come into use, and interest has arisen in their efficiencies under Ohio conditions.

Among the factors affecting both the need for phosphates and their comparative efficiencies, soil reaction and the nature of the crop have been recognized as having major importance. The present bulletin deals primarily with the effects of liming upon the response to phosphates and the efficiency of different phosphates on the naturally acid Wooster and Canfield silt loams.

Four groups of experimental data will receive consideration in order as follows: (a) Data from several long-time field experiments showing changes in the relative efficiencies of superphosphate, bone meal, basic slag, and rock phosphate with repeated liming over a period of years; (b) data from the Legume-Reaction Experiment showing the response of crops to superphosphate on soil adjusted to five different reactions; (c) data from a one-year field experiment in which the efficiencies of eight different phosphates, measured in terms of wheat yields, were determined on soil adjusted to three different reactions; (d) data from a greenhouse pot experiment in which the efficiencies of 11 phosphates, measured in terms of phosphoric acid removed in six successive cuttings of Sudan grass, were determined at two soil reactions.

THE EFFECTS OF REPEATED LIMING UPON THE EFFICIENCY OF PHOSPHATES IN LONG-TIME FIELD EXPERIMENTS

Several of the older field experiments at Wooster afford an opportunity for studying changes in the comparative efficiencies of superphosphate, bone meal, basic slag, and rock phosphate over a period of years during which the soil has been made progressively more alkaline by repeated liming.

The Five-Year Rotation Fertility Experiment, begun in 1894, includes four plots receiving equal amounts of nitrogen and potash fertilizers. One of these receives no phosphoric acid. Equal amounts of phosphoric acid have been applied to the other three plots—to one in the form of 16% superphosphate, to the second in the form of steamed bone meal, and to the third in the form of basic open-hearth slag. Beginning in 1900, one-half of each plot has been regularly limed for corn.

The Barnyard Manure Experiment, comprising a 3-year rotation of corn, wheat, clover, begun in 1897, includes two comparisons of equal amounts of 16% superphosphate and raw rock phosphate. In one case these materials are used in combination with unleached stall manure and in the other case with exposed yard manure.

In the Lime and Floats Experiment, begun in 1905, equal amounts of 16% superphosphate and raw rock phosphate are applied to corn in a corn, oats, clover rotation. In one comparison these materials are used alone, in a second with muriate of potash, and in a third with muriate of potash and burned lime.

The Four-Year Rotation Fertility Experiment, begun in 1915, includes a comparison of superphosphate and basic slag, each used to supply the phosphoric acid in a 4-8-4 complete fertilizer. These treatments were changed in 1926 so that the comparison ends in that year. This experiment also includes a comparison of rock phosphate and superphosphate, used in approximately equal money value quantities, as supplements to barnyard manure.

THE FIVE-YEAR ROTATION FERTILITY EXPERIMENT

In this experiment the rotation is corn, oats, wheat, clover, timothy; there are five sections, thus permitting the growing of all crops each year. Four plots are of interest in the present study. The treatments given these plots regularly throughout the 40-year period, 1894-1933, are shown in Table 1.

TABLE 1.—Treatment of Plots in Five-year Rotation Experiment

Plot No.	Materials	Nutrients applied per acre each rotation								
		Phosphoric acid (P_2O_5)			Potash (K_2O)			Nitrogen (N)		
		Corn	Oats	Wheat	Corn	Oats	Wheat	Corn	Oats	Wheat
		Lb.	*Lb.*	*Lb.*	*Lb.*	*Lb.*	*Lb.*	*Lb.*	*Lb.*	*Lb.*
9	Nitrate of soda * ..... Muriate of potash	......	....	....	40	40	50	24.8	24.8	24.8
11	16% superphosphate.. Nitrate of soda * ..... Muriate of potash	25.6	25.6	25.6	40	40	50	24.8	24.8	24.8
26	Steamed bone meal... Nitrate of soda*†..... Muriate of potash	25.6	25.6	25.6	40	40	50	24.8	24.8	24.8
29	Basic slag (18%) ..... Nitrate of soda * ..... Muriate of potash	25.6	25.6	25.6	40	40	50	24.8	24.8	24.8

*Prior to 1921, one-fourth of the nitrogen on wheat was applied as dried blood at seeding time and the remainder as nitrate of soda in the spring. Beginning in 1921, all nitrogen on wheat was applied as nitrate of soda at seeding time.

†Quantity of nitrate of soda applied is reduced as needed to allow for the nitrogen carried in the bone meal.

The regular liming of one-half of each plot as it went to corn was begun in 1900, quicklime being used on the west end of Section E in that year. During the next 4 years, lime was applied to the west ends of the other sections as they came to corn. In 1905, lime was applied to the east end of Section E and in 1906 and 1907 to the east ends of Sections A and B. Beginning in 1908, the lime treatments were returned to the west ends and have remained there since that time. Thus, two sections, C and D, have received lime only on the west ends; whereas three sections, A, B, and E, received one application on the east end, the effects of which have practically disappeared during the later years of the experiment. Burned lime was applied up to 1906 and ground limestone since then. The quantities applied have varied somewhat, but the average on all sections has been close to 2 tons of limestone equivalent each rotation.

No data are available on the reaction characteristics of the soil at the time liming was begun. Average data for samples representing the upper 7 inches of soil for five scattered plots of Section D, taken at the beginning of the experiment in 1894, and for the check plots of both limed and unlimed ends of Section D, taken in 1925 after 32 years of cropping, are presented in Table 2.

TABLE 2.—Reaction Characteristics of Surface Soils of Section D, Five-year Rotation Experiment

Year	Plots averaged	Reaction	Jones lime requirement	Calcium carbonate	Exchange hydrogen*	Degree of base saturation*
		pH	*Lb. $CaCO_3$ equiv. per A.*	*Lb. per A.*	*Lb. $CaCO_3$ equiv. per A.*	*Pct.*
1894	10, 11, 16, 19, 20	5.03	2526		4600	51
1925	All checks unlimed......	4.76	3942†	....	6110	24
1925	All checks limed	7.50	....	1430	15	94

*Data of Schollenberger, obtained by extraction with normal ammonium acetate at pH 7.07.

†Average of only three plots, Numbers 10, 16, and 19.

Since the soil of the other sections was probably similar to that of Section D at the beginning of the experiment, it may be assumed from the data in Table 2 that the soil as a whole was probably not above pH 5 at the time liming was begun in 1900. Since that time, the unlimed and untreated plots have become somewhat more acid; whereas the limed plots have become progressively more alkaline and are now considerably on the alkaline side of neutrality, with some free carbonate of lime present.

As the basis for comparing the efficiencies of the three phosphates, the yearly increases in yield for each crop on Plots 11, 26, and 29 were determined by deducting from the actual yields the theoretical unfertilized yields calculated from the appropriate check-plot yields by the usual progressive method. From the increases thus obtained was deducted the increase similarly found for Plot 9 which received only nitrogen and potash, the difference being ascribed to the phosphate. This method assumes that the effects of the different nutrients is additive, a relation shown by Thorne (23) to be approximately true for this experiment. In Figures 1 to 5, inclusive, are shown graphically the running 5-year average increases for each phosphate on both limed and unlimed land, each figure showing the results for a single crop. By plotting the running 5-year averages, the large fluctuations due to seasonal influences are partly eliminated and the long-time trends in efficiency are more easily recognized.

Since the trend in phosphate response is not necessarily associated with the trend in total yield and since it is interesting in some cases to compare the two, data on average yields for the entire period since liming was begun and for the last 10-year period are presented in Table 3.

The predominant position of the superphosphates among phosphate carriers used in Ohio makes the results with this material of particular interest[1]. Reference to the superphosphate curves in Figures 1 to 5, inclusive, shows a tendency for superphosphate to give larger increases for the three

[1]Superphosphates supplied 95.5 per cent of all the phosphoric acid applied unmixed to Ohio soils in 1933. Bone meal supplied 2.4 per cent and basic slag 2.1 per cent. It is probable that superphosphate supplied fully as large a proportion of the phosphoric acid applied in the form of mixed fertilizers.

grain crops on unlimed land than on limed land. This tendency is notable for oats and corn and in both cases appears to become more marked with increasing time; this tendency, previously noted, is associated with an increasing spread in reaction between the limed and unlimed soils. The increases plotted in Figures 1 to 5 are the absolute increases in bushels of grain or pounds of hay. If the increases are expressed as percentages of the unphosphated yield (Plot 9), the tendency for superphosphate to increase in effectiveness on the unlimed land and to decrease in effectiveness on the limed land is accentuated and shows up for all crops. This method of stating the increase for phosphate as a "relative effect" probably gives the most reliable indication of the effect of lime versus no lime on the efficiency of phosphates. In Figure 6 the running 5-year average percentage increases for corn and clover are shown, together with the linear regressions of percentage increase on time.

TABLE 3.—Yields in Five-year Rotation Experiment

Crop	Plot No.	Fertilizer treatment	Yield in bushels or pounds per acre					
			Unlimed			Limed		
			Entire period	Last 10 years	Difference	Entire period	Last 10 years	Difference
Corn	Checks, av.	None	19.2	11.3	— 7.9	30.7	27.6	— 3.1
	9	N, K	27.7	18.5	— 9.2	45.3	46.7	1.4
	11	N, K, P as superphosphate	41.9	33.3	— 8.6	55.4	55.6	0.2
	26	N, K, P as bone meal	39.3	30.9	— 8.4	51.8	50.6	— 1.2
	29	N, K, P as basic slag	42.3	34.7	— 7.6	51.8	51.5	— 0.3
Oats	Checks, av.	None	25.5	20.0	— 5.5	35.2	36.4	1.2
	9	N, K	32.2	27.3	— 4.9	43.0	44.7	1.7
	11	N, K, P as superphosphate	49.6	48.6	— 1.0	52.1	53.6	1.5
	26	N, K, P as bone meal	46.1	41.8	— 4.3	47.8	46.6	— 1.2
	29	N, K, P as basic slag	47.0	43.1	— 3.9	49.0	49.0	0.0
Wheat	Checks, av.	None	9.6	7.4	— 2.2	15.4	16.2	0.8
	9	N, K	12.6	10.6	— 2.0	18.6	19.5	0.9
	11	N, K, P as superphosphate	28.5	28.6	0.1	33.2	36.0	2.8
	26	K, K, P as bone meal	26.6	27.4	0.8	25.2	23.8	— 1.4
	29	N, K, P as basic slag	28.5	28.5	0.0	29.8	32.4	2.6
Clover	Checks, av.	None	948	624	—324	1923	2030	107
	9	N, K	1203	732	—471	2393	2559	166
	11	N, K, P as superphosphate	2221	1851	—370	3443	3674	231
	26	N, K, P as bone meal	2307	1796	—511	3440	3223	—217
	29	N, K, P as basic slag	2756	2640	—116	3438	3782	344
Timothy	Checks, av.	None	1502	1167	—335	2517	2709	192
	9	N, K	1702	1382	—320	2795	3091	296
	11	N, K, P as superphosphate	2346	2129	—217	3349	3578	229
	26	N, K, P as bone meal	2205	1994	—211	3603	3839	236
	29	N, K, P as basic slag	2639	2668	29	3470	3824	354

Two possible explanations may be advanced for the effects mentioned. It may be assumed that the availability of the native phosphorus of the soil increases in passing from an acid to an alkaline reaction, with a corresponding decrease in the need for fertilizer additions, or it is possible that the availability of the phosphorus supplied as superphosphate decreases as the reaction is made more alkaline, and vice versa. Evidence will be presented later indicating that both explanations may be correct, there occurring both an increase in the availability of the soil phosphorus and a decrease in availability of the added superphosphate with decreasing acidity or increasing alkalinity.

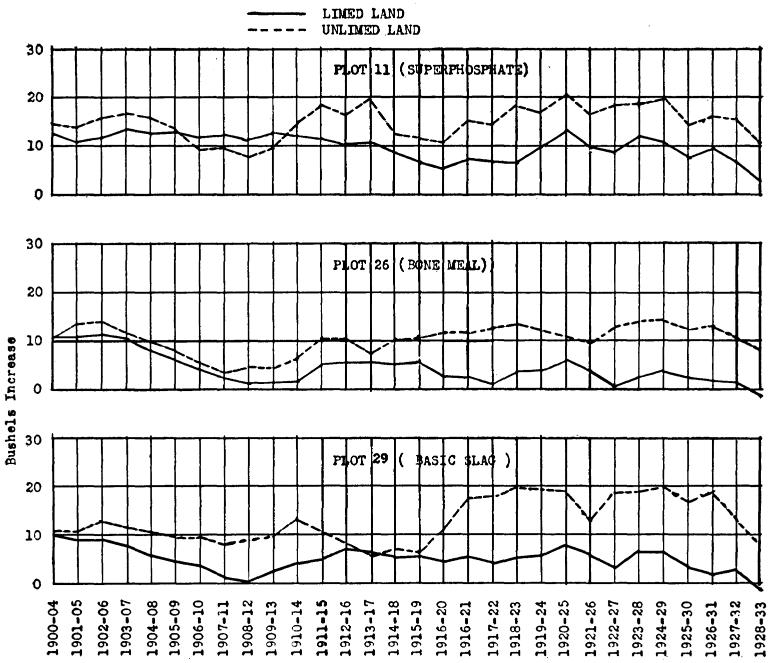

Fig. 1.—The efficiency of different phosphates as measured by increases in the yield of corn on limed and unlimed land in the Five-year Rotation Fertility Experiment

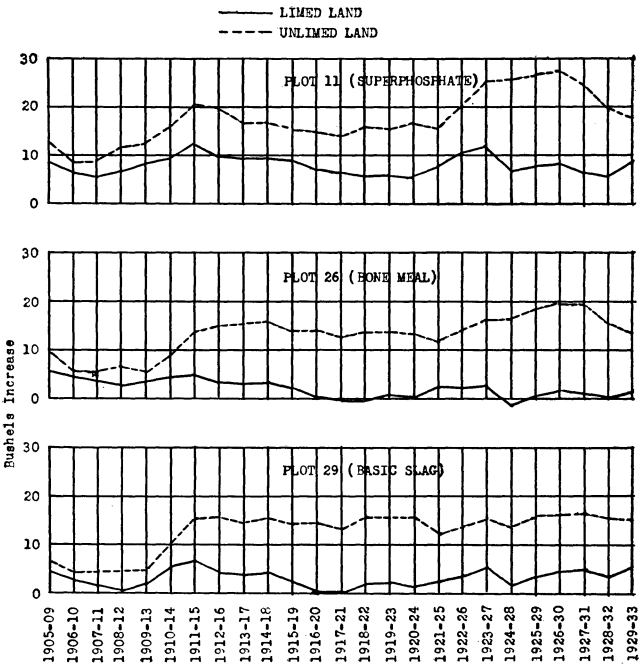

Fig. 2.—The efficiency of different phosphates as measured by increases in the yield of oats on limed and unlimed land in the Five-year Rotation Fertility Experiment.

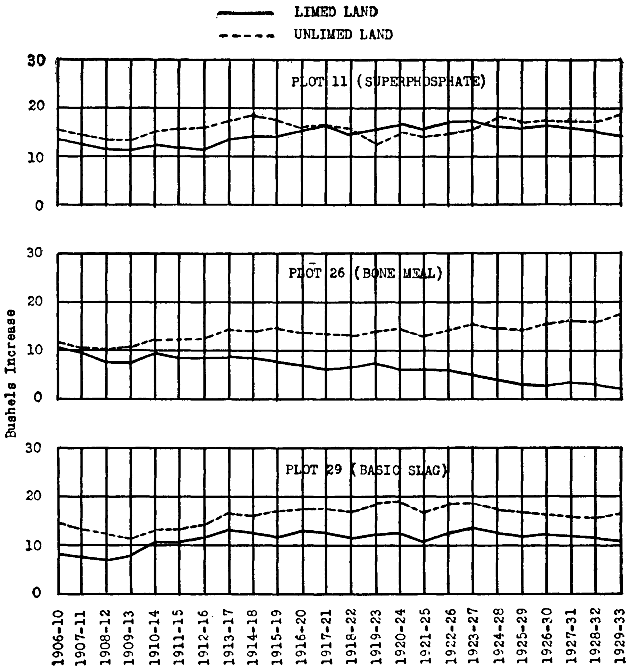

Fig. 3.—The efficiency of different phosphates as measured by increases in the yield of wheat on limed and unlimed land in the Five-year Rotation Fertility Experiment.

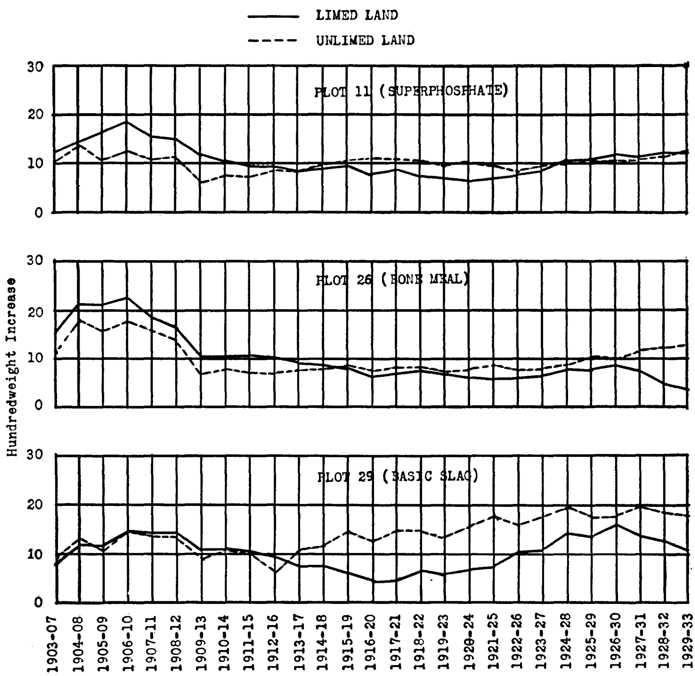

Fig. 4.—The efficiency of different phosphates as measured by increases in the yield of clover on limed and unlimed land in the Five-year Rotation Fertility Experiment

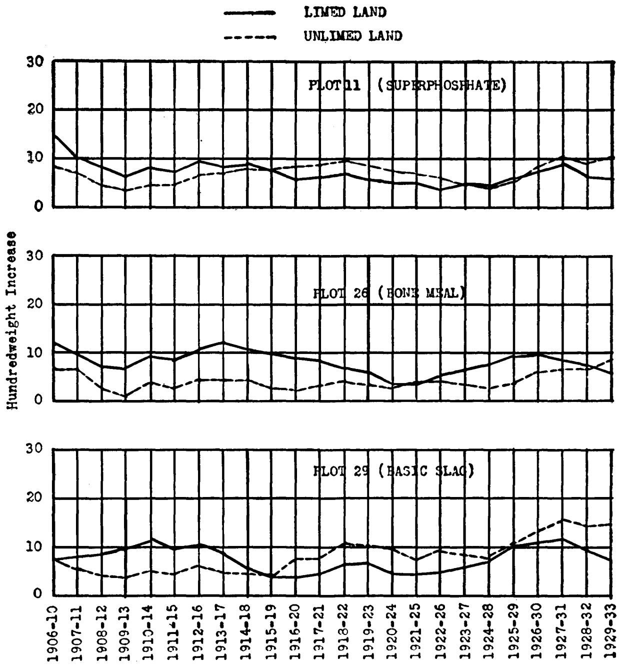

Fig. 5.—The efficiency of different phosphates as measured by increases in the yield of timothy on limed and unlimed land in the Five-year Rotation Fertility Experiment.

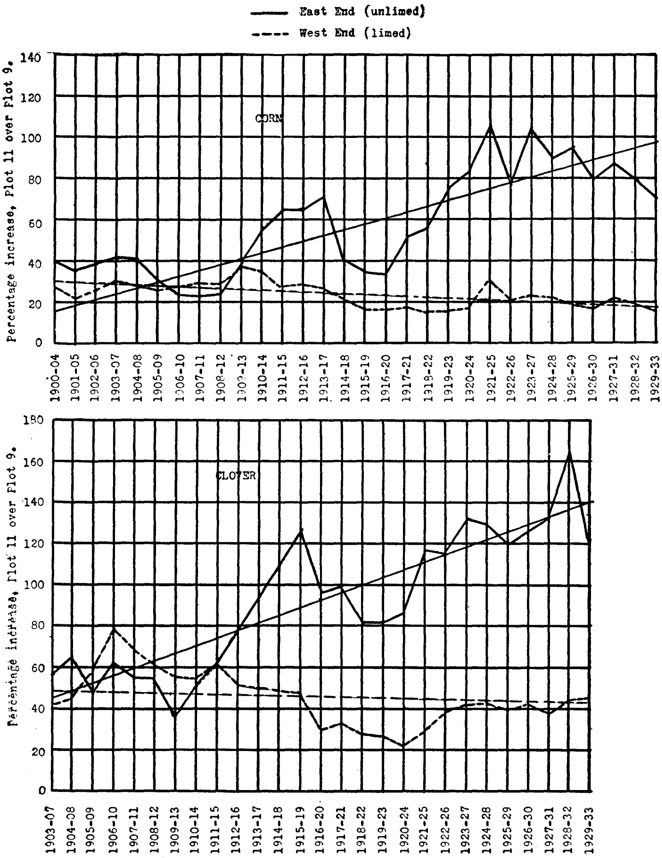

Fig. 6.—Running 5-year average percentage increases of corn and clover for limed and unlimed ends of Plot 11 (N, P, K) over corresponding ends of Plot 9 (N, K); also linear regressions of percentage increases on time.

The efficiency relationships of bone meal and basic slag will be discussed by comparing these materials with superphosphate. In considering the response to bone meal and basic slag on the unlimed soil, attention should be called to the fact that both of these materials are basic in character and possess a certain neutralizing effect not possessed by superphosphate which has practically no effect on soil reaction[2]. The "equivalent basicity" in terms of calcium carbonate was determined by the method of Pierre (15) for the materials used in recent years in this experiment and was found to be 820 pounds per ton for the bone meal and 1480 pounds per ton for the basic slag. Thus, the 285 pounds of bone meal applied each rotation had a potential lime effect equivalent to 117 pounds of limestone, or equal to 936 pounds of limestone during the entire 40 years. Similarly, the 435 pounds of basic slag

[2]Extensive studies of teeth and bones by Gassman (6) indicate that bone is a carbonate-phosphate having the empirical formula 3 $Ca_3(PO_4)_2 \cdot CaCO_3$. X-ray studies of De Jong (2) tend to support this idea, although Kramer and Shear (12) report that the carbonate content of bones increases with the age of the animal.

applied each rotation had a potential lime effect equivalent to 322 pounds of limestone, or equal to 2576 pounds of limestone during the 40-year period. These small amounts of lime have produced no notable changes in the reaction of the soil, although determinations made on Sections C and D in 1925 showed average increases in pH above adjacent check plots of 0.17 pH for the bone meal and 0.28 pH for the basic slag, as compared with a similar increase of only 0.06 for superphosphate. That the lime supplied by these phosphates has appreciably improved the lime-sensitive clover crop (especially in the case of basic slag) is evident from the comparison of the relative increases for clover as against the grain crops for the entire period, as shown in Table 4. That the superiority of basic slag to superphosphate for clover has increased with the duration of the experiment is evident from Figure 4. It is also shown by the fact that, during the last 10 years, basic slag has given a 70 per cent greater increase than superphosphate, as compared with a 38 per cent greater increase for the entire period. The superior growth of clover on the unlimed, basic-slag plot has been regularly noticeable in the field.

TABLE 4.—Increases for Phosphates on Unlimed Plots in the Five-year Rotation Experiment for the Period 1900 to 1933, Inclusive

Phosphate	Average increase in yield per acre*				
	Corn	Oats	Wheat	Clover	Timothy
	Bu.	*Bu.*	*Bu.*	*Lb.*	*Lb.*
16% superphosphate	14.7	17.4	16.1	1018	723
Steamed bone meal	10.3	13.0	13.9	1020	435
Basic slag	12.8	12.8	15.9	1408	861
Relative increases					
16% superphosphate	100	100	100	100	100
Steamed bone meal	70	75	86	100	60
Basic slag	87	74	99	138	119

*Increases are for the N, P, K plots over the N, K plot.

It is improbable that the response to bone meal and basic slag on the limed plots has been appreciably affected by any direct influence of the relatively small amounts of lime carried. Hence, the increases shown in Figures 1 to 5, inclusive, may be considered as indicating the actual comparative availabilities of phosphoric acid in the three phosphates. The same applies to the data in Table 5 which shows the average increases for the different phosphates on the limed land for the entire period since liming was begun.

The relative increases presented in Tables 4 and 5 may be considered as efficiency indices based on superphosphate taken as 100. Considering the results for the three grain crops, which were directly fertilized and probably little affected by the basicity of the bone or slag, the average efficiency index for bone meal is 77 on the unlimed soil and 41 on the limed soil, an indicated decrease of 46 per cent in the efficiency of bone meal due to liming. Similarly for basic slag, the average efficiency index on unlimed soil is 87 and on limed soil 59, a decrease of 31 per cent in efficiency from the lime treatment. Reference to the graphs (Figs. 1 to 5, inclusive) shows a downward trend in the increase curves for bone meal for all crops excepting timothy, indicating a marked tendency for bone meal to decrease in effectiveness with repeated liming. This decrease has been particularly consistent in the case of wheat. Table 3 shows that the yield of wheat on the limed bone meal plot for the last 10 years has actually averaged 3.6 bushels less than on the corresponding unlimed plot—meaning, of course, that the reduced efficiency of bone meal on the limed soil has more than offset any benefit to the crop from liming. During the same period, superphosphate with lime has produced 7.4 bushels more wheat than superphosphate without lime, and basic slag with lime, 3.9 bushels more than basic slag without lime.

TABLE 5.—Increases for Phosphates on Limed Plots in the Five-year Rotation Experiment for the Period 1900 to 1933, Inclusive

Phosphate	Average increase in yield per acre*				
	Corn	Oats	Wheat	Clover	Timothy
	Bu.	*Bu.*	*Bu.*	*Lb.*	*Lb.*
16% superphosphate	9.7	8.5	14.5	1074	677
Steamed bone meal	4.5	2.8	6.6	968	780
Basic slag	4.9	4.2	11.3	993	673
Relative increases					
16% superphosphate	100	100	100	100	100
Steamed bone meal	46	33	45	90	115
Basic slag	51	50	78	92	99

*Increases are for the N, P, K plots over the N, K plots.

Both bone meal and basic slag have given better results, as compared with superphosphate, on the hay crops than on the grain crops. This might indicate (a) a greater residual effect due to less complete utilization by the grain crops, (b) better utilization of these less soluble phosphates by the hay crops, or (c) less rapid fixation in the form of insoluble combinations in the soil. It is possible that all three factors were operative.

THE BARNYARD MANURE EXPERIMENT

This experiment comprises three sections cropped to a rotation of corn, wheat, and clover. Six plots are of interest in the present study. The treatments given these plots regularly throughout the 37-year period 1897-1933 are shown in Table 6.

TABLE 6.—Treatment of Plots in Barnyard Manure Experiment

Plot No.	Material	Rate of application per acre (all on corn)
2	Yard manure Rock phosphate*	8 tons 320 lb.
3	Stall manure Rock phosphate*	8 tons 320 lb.
5	Yard manure 16% superphosphate	8 tons 320 lb.
6	Stall manure 16% superphosphate	8 tons 320 lb.
15	Yard manure	8 tons
16	Stall manure	8 tons

*Prior to 1927 the rock phosphate used contained approximately 28 per cent of P_2O_5 and 65 per cent of material passing a 100-mesh screen. Since 1927 Ruhm's rock phosphate, containing about 33 per cent of P_2O_5 and 97 per cent of material passing a 100-mesh screen, has been used.

Liming was begun in 1905 and, except for some irregularities in the earlier years, has been repeated each rotation at the rate of 2 tons of ground limestone per acre, the lime being applied to the corn crop. Information on the reaction of the soil at the beginning of the experiment is lacking. Samples taken from Section A in 1912 after three limings, totalling 5 tons per acre, show a reaction of approximately pH 5.75. Probably, the reaction at the start was at least as low as pH 5.0. At the present time, the reaction of all plots is close to pH 7.7.

As the measure of effectiveness of the two phosphates, the yearly increases in yield on the plots receiving yard manure and stall manure were deducted from the increases on the plots receiving the same manure treatments with either rock phosphate or superphosphate in addition. The increases over stall and yard manure were averaged to give a single value for each phosphate. A running 6-year average of these yearly values for each crop is plotted in Figure 7.

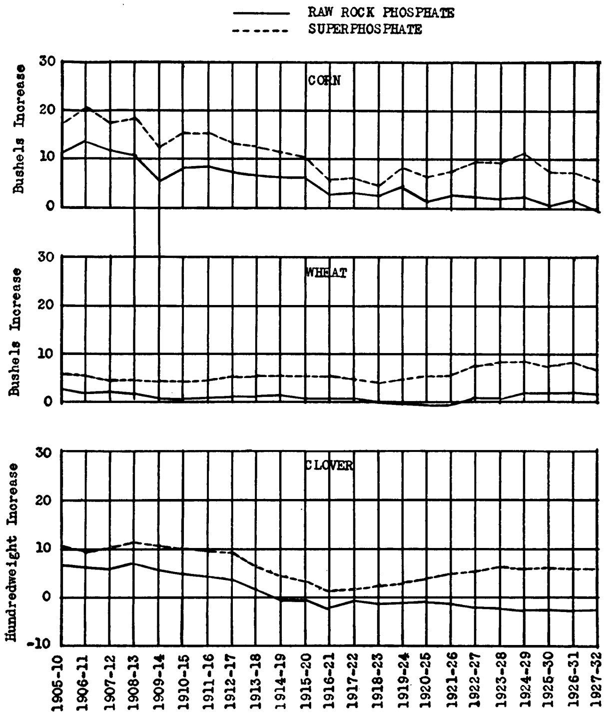

Fig. 7.—Relative efficiencies of rock phosphate and superphosphate as measured by crop increases over a period of years during which the soil reaction changed from acid to alkaline. Barnyard Manure Experiment.

From Figure 7 it is apparent that the effectiveness of superphosphate decreased notably in the case of corn and appreciably in the case of clover as the duration of the experiment increased and the soil became more alkaline. The absolute increases in wheat have increased somewhat, but the yield of wheat increased considerably toward the latter part of the experiment on the plots receiving manure alone. If the increases for superphosphate are stated as percentages of the unphosphated yields, there is a decrease in efficiency with all crops, thus corroborating the evidence from the Five-year Rotation Experiment that continued liming either reduces the need for phosphoric acid or lowers the availability of the phosphoric acid in superphosphate.

It is evident from the figure that rock phosphate, although supplying nearly double the amount of total phosphoric acid carried in the superphosphate, has been consistently less effective. Throughout the experiment it has proven a poor source of phosphoric acid for wheat, its effect being, in fact, to decrease rather than increase the yield in some years. In the earlier years, when the reaction of the soil was still acid, rock phosphate was moderately effective on corn and clover, but with progressive increase in alkalinity its effect has fallen off markedly, approaching zero during the later years for corn and actually reducing the yield of clover during the later half of the experiment. It is interesting that the larger residues of phosphoric acid accumulating in the soil from the rock phosphate treatments have not led to any enhancement of the returns from this material. Soil samples taken from 0 to 7 inches on Section A in 1925 showed 975 pounds of total phosphorus per acre as an average for the plots receiving rock phosphate, 846 pounds for the superphosphate plots, and 830 pounds for the plots receiving manure only. In 1910, Hopkins (9) commented on this experiment as follows: "It should be kept in mind that 320 pounds of raw phosphate contains 40 pounds of phosphorus, while 320 pounds of acid phosphate (superphosphate) contains about 20 pounds of that element, so that the raw phosphate is enriching the soil in phosphorus twice as much as the acid phosphate, while the removal in crops is practically equal." The anticipated enrichment of the soil has actually taken place, but apparently the depressing effect of increasing alkalinity has more than offset its effect insofar as the crops are concerned.

TABLE 7.—Comparison of Increase for Rock Phosphate Before and After Changing to a Finer Ground Phosphate

	Average increase in yield per acre					
	Corn		Wheat		Clover	
	Yr.	*Bu.*	*Yr.*	*Bu.*	*Yr.*	*Lb.*
Coarsely ground rock phosphate*.....	1921–26	—1.0	1923–27	0.6	1925–28	—158
Finely ground rock phosphate†	1927–32	0.3	1928–32	0.8	1929–32	—325

*Approximately 60 per cent passing a 100-mesh screen.
†Approximately 97 per cent passing a 100-mesh screen.

Since 1927 the rock phosphate used has been much more finely ground than that used prior to that time. In Table 7 are shown the average increases for rock phosphate since that time and for comparison the average increases for a corresponding number of years prior to the change.

While the time periods are too short to permit definite conclusions, these data give no evidence of any improvement in the efficiency of the rock phosphate from changing to the finer product.

THE LIME AND FLOATS EXPERIMENT

This experiment, begun in 1905, comprises three sections cropped to a rotation of corn, oats, hay. The hay crop was a mixture of red and alsike clovers from 1906 to 1921, inclusive, excepting 1906, 1908, and 1909 when soybeans were substituted because of clover failures. From 1922 to 1929, inclusive, the hay crop was a mixture of sweet clover and alfalfa (the former greatly predominating), except on the unlimed plots where little or no sweet clover or alfalfa has grown; the yields on these plots have been made up largely of grasses and weeds. In the years 1930, 1931, and 1932 alfalfa was grown on one-half and sweet clover on the other half of each plot, the average yields for the two crops being employed in the present study. Prior to the beginning of the experiment the land had been under a good cropping program, had received considerable manure, and was in good condition although no lime had been applied. Samples of surface soil taken on Section A in 1925 showed, as an average for 16 unlimed plots, a reaction of pH 5.36. The corresponding plots of Section C gave an average reaction of pH 5.21 in 1933. No information is available as to the reaction of the soil at the beginning of the test, but samples taken in 1912 and stored show reactions around pH 5.3 for the unlimed plots. The comparatively good yields of clover obtained in the earlier years indicate that the reaction may have been somewhat less acid at the beginning.

Six plots giving three comparisons of superphosphate and rock phosphate are of interest in the present study. Their treatments are shown in Table 8.

TABLE 8.—Treatment of Plots in Lime and Floats Experiment

Plot No.	Material	Rate of application per acre (all on corn)
		Lb.
20	16% superphosphate	320
23	Rock phosphate	320
21	16% superphosphate	320
	Muriate of potash	40
24	Rock phosphate	320
	Muriate of potash	40
17	16% superphosphate	320
	Muriate of potash	40
	Quicklime*	1000
18	Rock phosphate	320
	Muriate of potash	40
	Quicklime*	1000

*An equivalent amount of hydrated lime used since 1926.

The 6-year running averages for the increases from superphosphate on Plot 20 and for rock phosphate on Plot 23 are shown graphically for each crop of the rotation in Figure 8. Similar graphs for the remaining plots are not given since it is not possible to separate the effect of the phosphates from that of the muriate of potash and lime used in addition, there being no plots receiving these materials in similar amounts without the phosphates. However, the total yields and increases for these plots are shown in Table 9 for three periods of 9 years, or three rotations each.

The yields of all unmanured plots in this experiment declined markedly during the earlier years. This decline continued throughout the experiment on all of the unlimed plots, but on the limed plots the yields of hay and corn improved somewhat after 1922, when sweet clover and alfalfa were substituted for the common clovers. This situation is indicated by comparing the yields of the limed and unlimed plots in Table 9 for the three successive 9-year periods, the third period agreeing approximately with that during which alfalfa and sweet clover have been grown. These large changes in productivity of the land with time render difficult the interpretation of the comparative efficiency of the two phosphates. Judging by Figure 8, superphosphate when used alone has given somewhat larger average increases than rock phosphate, except on the hay crop where rock phosphate has been slightly more effective since about 1915. From that time the hay grown on these plots has contained very little clover. As a whole, the efficiency of the rock phosphate appears to have increased somewhat as compared to superphosphate with the increasing duration of the experiment, probably reflecting an increase in the acidity of the soil.

TABLE 9.—Yields and Increases for Plots in Lime and Floats Experiment

Plot No.	Treatment*	Period†	Corn Yield	Corn Increase	Oats Yield	Oats Increase	Hay Yield	Hay Increase
			Bu.	*Bu.*	*Bu.*	*Bu.*	*Lb.*	*Lb.*
21	Superphosphate, 320 lb..... Muriate of potash, 40 lb.....	1	66.2	14.8	47.9	3.1	4443	413
		2	45.8	15.1	47.1	7.7	2017	269
		3	38.5	12.6	36.8	9.2	1077	122
24	Rock phosphate, 320 lb..... Muriate of potash, 40 lb.....	1	56.6	8.9	44.8	1.3	3912	54
		2	40.7	12.0	42.3	6.2	1872	382
		3	35.4	11.9	34.6	9.7	1064	228
17	Superphosphate, 320 lb..... Muriate of potash, 40 lb..... Quicklime, 1000 lb.....	1	70.4	20.1	50.6	5.4	5084	1264
		2	55.3	23.5	56.9	16.1	4049	2105
		3	59.0	30.7	53.9	23.1	4407	3269
18	Rock phosphate, 320 lb..... Muriate of potash, 40 lb..... Quicklime, 1000 lb.....	1	66.4	15.4	48.4	3.2	4991	1091
		2	49.7	17.6	53.3	12.2	3719	1810
		3	56.4	28.4	47.6	17.6	4435	3344

*All treatments on corn.
†Period 1, 1905-1913; Period 2, 1914-1922; Period 3, 1923-1931.

That the same comment applies to the efficiency of the combination of rock phosphate and muriate of potash used on Plot 24 is evident when the data for this plot are compared with those for Plot 21 in Table 9. Comparing the limed plots, 17 and 18, with the unlimed plots, 21 and 24, indicates no marked change in the relative efficiency of the rock phosphate – potash treatment due to liming. The amounts of lime used have been moderate and the limed soil has not attained the degree of alkalinity noted in the experiments previously discussed. Samples of the surface soil of Plots 17 and 18 taken from Section A in 1925 both showed a reaction of pH 7.0. Similar samples taken from Section C in 1933 gave an average reaction of pH 6.6.

It is worthy of note that the effectiveness of both phosphates improved considerably on the limed plots during the third period, after the introduction of sweet clover and alfalfa. Of particular interest is the fact that the yield and increase of hay for the third period on Plot 18 receiving rock phosphate actually exceed those on Plot 17 receiving superphosphate; whereas the opposite relation existed in the first two periods. This probably reflects the greater ability of sweet clover and alfalfa, primarily the former, to feed upon rock phosphate than of the common clovers. Associated with this increase in hay for rock phosphate is a relatively large increase in corn, even though the hay was taken off.

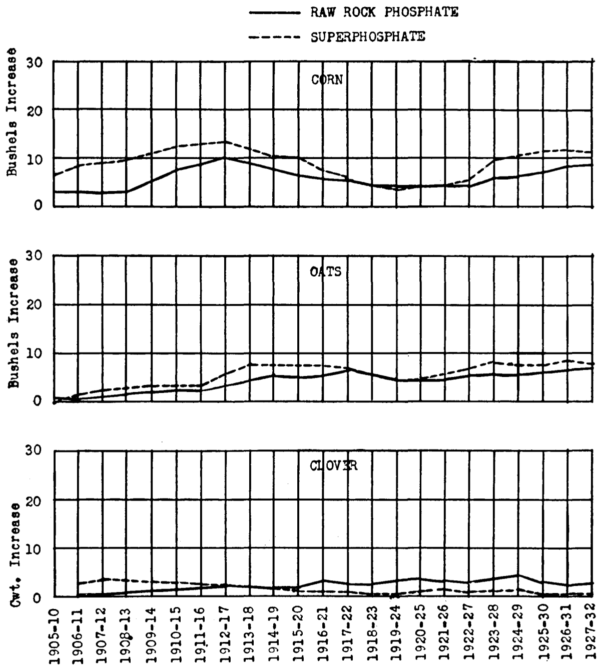

Fig. 8.—Relative efficiencies of rock phosphate and superphosphate as measured by crop increases over a period of years during which no lime was applied. Lime and Floats Test.

THE FOUR-YEAR ROTATION FERTILITY EXPERIMENT

In this experiment, begun in 1915, corn, oats, wheat, and clover have been grown in rotation on four sections of land. Ground limestone has been applied each rotation on corn at the rate of 2 tons per acre. No data are available on the reaction of the soil at the beginning of the experiment. Adjacent land similarly cropped for the same period and receiving regular applications of manure and superphosphate but no lime has at present a reaction of about pH 5.2. The plots under consideration now show a reaction in the surface soil of about pH 7.2. Two pairs of plots are of interest in the present study. Their treatments are shown in Table 10.

TABLE 10.—Treatment of Plots in Four-year Rotation Fertility Experiment

Plot No.	Material	Application per acre	
		Corn	Wheat
17	4-8-4, phosphoric acid supplied as superphosphate*	500 lb.	500 lb.
20	4-8-4, phosphoric acid supplied as basic slag*	500 lb.	500 lb.
33	Yard manure	8 tons	....
	16% superphosphate†	480 lb.	....
38	Yard manure	8 tons	....
	Rock phosphate‡	768 lb.	....

*Treatments changed in 1926; no comparison possible since that time.
†Beginning in 1926 superphosphate divided equally between corn and wheat.
‡Superfine grade of rock phosphate used in 1926 and since.
Note: The phosphate application on Plots 33 and 38 represented equal money values at the beginning of the experiment.

In this experiment it is not possible to differentiate between the effects of the phosphates and that of the supplementary chemicals or manure. Hence, direct comparison of their efficiencies cannot be made. In Table 11 are presented the average yields and increases, divided into two periods, for each pair of plots.

TABLE 11.—Yields and Increases in Four-year Rotation Fertility Experiment

Plot No.	Treatment		Corn		Oats		Wheat		Clover	
			Yield	Increase	Yield	Increase	Yield	Increase	Yield	Increase
			Bu.	*Bu.*	*Bu.*	*Bu.*	*Bu.*	*Bu.*	*Lb.*	*Lb.*
17	4-8-4*, phosphoric acid supplied as superphosphate	1915-1921	66.4	13.4	54.2	3.6	35.9	13.2	4283	659
		1922-1926	72.3	18.3	63.9	10.2	41.7	16.7	3879	1350
20	4-8-4*, phosphoric acid supplied as basic slag	1915-1921	64.7	11.6	54.8	3.1	34.9	13.1	4158	382
		1922-1926	68.0	15.3	63.9	9.2	42.5	16.7	3785	1240
33	Manure and superphosphate†	1915-1925	72.6	20.0	59.4	8.1	32.5	9.4	4074	815
		1926-1933	69.6	25.7	52.2	8.8	37.3	16.1	4236	1099
38	Manure and rock phosphate‡	1915-1925	69.9	13.6	57.7	4.4	28.2	5.1	3660	308
		1926-1933	68.8	23.7	55.9	9.8	28.1	7.3	3744	506

*Applied 500 pounds per acre on both corn and wheat.
†Eight tons manure on corn and 480 pounds 16% superphosphate—all applied to corn during first period and divided equally between corn and wheat in second period.
‡Eight tons manure and 768 pounds rock phosphate applied to corn. Superfine rock phosphate used during second period.

From the increases in Table 11 it is observed that superphosphate has been somewhat more effective than basic slag throughout the experiment for all crops, excepting wheat, where there is no appreciable difference between the effects of the two phosphates in either period. The relative efficiencies of superphosphate and basic slag seem to have been little if at all affected by the repeated liming of the land.

Used in addition to manure, rock phosphate has been considerably less effective than superphosphate throughout the experiment. The change in the distribution of the superphosphate on Plot 33 and the use of a finer grade of rock phosphate on Plot 38 during the second period prevent any interpretation of the effect of repeated liming on the relative efficiencies of the two phosphates. The fact that larger increases were produced on both plots during the second period is probably due to the cumulative effects of the manure applications rather than to the changes in the phosphate treatments.

THE LEGUME-REACTION EXPERIMENT

In this experiment, begun in 1926, seven different hay crops are grown in 3-year rotation with corn and small grain over a series of ranges adjusted approximately to the following reactions—pH 4.5, pH 5, pH 6, pH 7, and pH 8. There are three sections, permitting the growing of all crops each year with the exception of the small grain crops, wheat, oats, and barley, each of which is grown on a single section and hence only once in 3 years. The soil is a Canfield silt loam which at the beginning of the test was rather low in fertility and had a reaction slightly above pH 5.0. Adjustment to higher pH values was made by appropriate additions of pulverized limestone and to lower pH values by applications of aluminum sulfate or sulfur. No manure has been applied, but muriate of potash, at the rate of 40 pounds per acre on corn and 50 pounds per acre on the small grains, has been applied to all ranges. In addition, one-half of each plot has received 200 pounds of 20% superphosphate broadcast on corn and 400 pounds on the small grains. The fertilizer treatment was intended to determine both the effect of liberal phosphate additions upon the reaction response of the crops grown and the relation of soil reaction to phosphate response. The pertinent data on yields and gains for superphosphate up to and including 1933 are presented in Table 12. The significance of the differences between the phosphated and unphosphated yields was calculated by Student's method and those giving odds in excess of 19 to 1 for significance are marked with an asterisk. The increases for superphosphate are stated in two ways; viz., (a) as pounds or bushels per acre, of particular importance in determining the relative economy of the phosphate application, and (b) as percentage increase over the unphosphated yield, probably the best indication of the comparative effectiveness of the applied phosphate at the different reactions. In interpreting the data in the table, it should be remembered that the soil reactions shown were the "intended" reactions and were only approximately attained. The average of five determinations of soil reaction, covering a period of 4 years, is given in a footnote to the table. It is apparent that the "intended" reactions were approximated rather closely except in the case of the intended reaction of pH 8, where, in spite of heavy additions of finely ground limestone (totalling 11.2 tons per acre in the 8 years), the reaction has exceeded pH 7.5 only since 1931.

It is worthy of note that on the unphosphated land 10 of the 11 crops gave their highest yields at the highest pH, corn being the single exception. On the phosphated land, eight of the 11 crops gave their highest yields at pH 7, and only in the case of sweet clover was the yield at pH 7 exceeded by the yield at the highest reaction. Apparently, the application of superphosphate

TABLE 12.—Yields and Increases for Superphosphate at Different Soil Reactions in the Legume-Reaction Experiment

Crop	Reaction† (intended)	Average yield per acre		Gain for superphosphate	
		Superphosphate	No phosphate		
	pH	*Bu. or Lb.*	*Bu. or Lb.*	*Bu. or Lb.*	*Per cent*
Corn	4.5	13.6	15.3	1.7	—11.1
	5.0	28.1	24.6	3.5*	14.2
	6.0	31.7	28.6	3.1	10.8
	7.0	37.8	35.6	2.2	6.2
	8.0	32.5	34.5	— 2.0*	— 5.8
Oats	4.5	70.4	59.8	12.6*	21.1
	5.0	70.1	55.1	15.0*	27.5
	6.0	70.8	55.8	15.0*	26.9
	7.0	69.8	65.8	4.0*	6.1
	8.0	69.8	69.3	0.5	0.7
Barley	4.5	0.0	0.0	....	....
	5.0	5.5	2.8	2.7*	95.5
	6.0	19.3	10.5	8.8*	84.9
	7.0	22.9	17.0	5.9*	34.7
	8.0	24.1	20.7	3.4*	16.4
Wheat	4.5	26.1	7.7	18.4*	239.0
	5.0	29.2	11.4	16.8*	67.8
	6.0	34.1	14.8	19.3*	76.7
	7.0	38.2	22.2	16.0*	72.1
	8.0	37.9	27.2	10.7*	39.3
Alfalfa	4.5	175	157	18	10.2
	5.0	515	623	— 108	—17.3
	6.0	1974	1748	226	12.9
	7.0	4923	3728	1195*	32.1
	8.0	4813	4691	122	2.6
Sweet clover	4.5	30	45	— 15	—33.4
	5.0	170	294	— 124*	—42.2
	6.0	2893	1504	1389*	92.4
	7.0	5774	3991	1783*	44.7
	8.0	6270	5320	950*	17.9
Red clover	4.5	572	682	— 110*	—16.3
	5.0	863	779	84	10.8
	6.0	1832	1355	477*	35.4
	7.0	3069	2408	661*	27.5
	8.0	2892	2895	— 3	— 0.1
Mammoth clover	4.5	642	1241	— 599	—48.3
	5.0	1151	1206	— 55	—45.6
	6.0	2453	1934	519*	26.8
	7.0	3661	2859	802*	28.0
	8.0	3279	3583	— 304	— 8.5
Alsike clover	4.5	516	718	— 202*	—28.1
	5.0	1096	883	213	24.1
	6.0	2792	1537	1255*	82.3
	7.0	3805	2506	1299*	51.9
	8.0	3513	3379	134	4.0

TABLE 12.—Yields and Increases for Superphosphate at Different Soil Reactions in the Legume-Reaction Experiment—Continued

Crop	Reaction† (intended)	Average yield per acre		Gain for superphosphate	
		Superphosphate	No phosphate		
	pH	*Bu. or Lb.*	*Bu. or Lb.*	*Bu. or Lb.*	*Per cent*
Timothy	4.5	827	751	76	10.1
	5.0	1205	1167	38	3.3
	6.0	1758	1299	459*	35.4
	7.0	2678	2228	450*	20.3
	8.0	2558	2382	176	7.4
Soybeans	4.5	1705	1794	— 89	— 4.9
	5.0	2049	2021	28	1.4
	6.0	1984	2029	45	2.2
	7.0	2625	2552	73	2.9
	8.0	2473	2656	— 183	— 6.9

Note: Averages given are for the following numbers of years and numbers of plots per year:

Corn, 5 years; oats, 1 year; wheat and barley, 2 years; all hay crops, 6 years.

All grain crops, 10 plots each year; red clover, 4 plots each year; all other hay crops, 1 plot each year.

*Values so marked have odds greater than 19:1 by Student's method that they are significantly greater or less than zero.

†The following is a comparison of the intended reactions and the actual reactions as an average of five sets of determinations covering a 4-year period.

Intended reaction	Actual reaction
pH	pH
4.5	4.7
5.0	5.2
6.0	5.9
7.0	6.8
8.0	7.4

has reduced the optimum pH for a majority of the crops studied. (See Fig. 9.) The response to phosphate for all crops is low at the highest pH whether measured in bushels and pounds or in percentage of the unphosphated yield. In five cases superphosphate has given an apparent decrease in yield at this reaction but only in the case of corn are the odds by Student's method high enough to indicate significance. With eight of the 11 crops, the response to phosphate on the percentage basis is also lower at pH 7 than at pH 6, the opposite being true only in the cases of alfalfa, mammoth clover, and soybeans. It would seem therefore that in general the effectiveness of superphosphate tends to decrease as the reaction of the soil is increased from pH 6 to pH 7 and higher. There is also a marked tendency for the effectiveness of superphosphate to decrease at the more acid reactions. Without exception the hay crops show a falling off, not only in the absolute increase for phosphate but also in the percentage increase in going from pH 6 to pH 5. In fact, with no single hay crop is the increase for phosphate at pH 5 large enough to be statistically significant. The three grain crops, corn, oats, and barley, show largest percentage increases for the phosphate at pH 5; whereas, with the exception of wheat, the response of all crops to the phosphate at pH 4.5 is either relatively low or negative. In the case of red and alsike clovers the decreases in yield for superphosphate at pH 4.5 give satisfactory odds for significance by Student's method.

Fig. 9.—Sweet clover and alfalfa on phosphated and unphosphated plots of pH 7 and pH 8. Ranges in Legume-Reaction Experiment. Photographed May 21, 1934

Since the effect of the phosphate treatment at pH 7 has been positive throughout and its effect at the highest reaction significantly positive in the case of wheat and barley and not significantly different from zero with all of the other crops except corn (which gave a small but apparently significant negative effect), it seems reasonable to conclude that the rather general decrease in yield on the phosphated soil in passing from pH 7 to the next higher reaction is not due to any detrimental effect of superphosphate on the alkaline soil and also that, where phosphorus is not a limiting factor, a reaction of about pH 7 is most favorable for a majority of the crops studied. On this basis it is perhaps fair to conclude that the improvement noted on the unphosphated soil with all crops except corn in passing from pH 7 to the highest pH is the result of an enhanced availability of the native soil phosphorus at the latter reaction. This suggests that the poor showing for superphosphate at this reaction may be due to the lack of any need for additional phosphorus rather than to a reduction in the availability of the applied phosphate, although there is no direct evidence that such a reduction did not occur.

THE PHOSPHATE-REACTION EXPERIMENT

A field experiment comparing eight different phosphates at three soil reactions was started in the spring of 1932. The original reaction of the soil, a Canfield silt loam, was about pH 5.5. One range was left without liming; a second and a third range received pulverized limestone calculated to raise their reactions to about pH 6 and pH 7, respectively. Each range was divided into four blocks of ten 0.007-acre plots each, each block including a single plot for each phosphate and two checks, all arranged at random. All plots excepting the checks received the equivalent of 250 pounds per acre of a fertilizer containing 4 per cent nitrogen, 12 per cent total phosphoric acid, and 8 per cent potash. The phosphoric acid was supplied in the form of the various phosphates, the potash as the muriate, and the nitrogen as sulfate of ammonia, the quantity of the latter being adjusted to allow for any nitrogen contained in the phosphates. The checks received the same amounts of nitrogen and potash but no phosphoric acid. Both limestone and fertilizers were applied broadcast after plowing and were incorporated during the preparation of the seedbed for a crop of oats which was grown and harvested for yield by plots. The weather was unfavorable for the oats crop and the effects of the fertilizer treatments were too small and too irregular to permit any reliable conclusions to be drawn concerning the comparative efficiency of the different phosphates. After harvesting the oats, samples of soil were taken from each plot in the three reaction ranges and their reactions determined. The land was plowed and the calculated amounts of pulverized limestone needed to adjust the soil to the desired reaction on Range 2 (pH 6) and Range 3 (pH 7) were applied and incorporated by disking. Each plot also received a second fertilizer treatment equal in amount and analysis to the spring treatment. Wheat was sown in the fall of 1932 and harvested by plots in the summer of 1933. After removing the wheat crop, all plots were again sampled and their reactions determined.

TABLE 13.—Composition of Phosphates Employed in the Phosphate-Reaction Experiment and the Final Soil Reactions

Material*	Content of		Average final soil reactions‡		
	Phosphoric acid (P_2O_5)	Nitrogen (N)	Range 1	Range 2	Range 3
	Pct.	*Pct.*	*pH*	*pH*	*pH*
Superphosphate	20.00	....	5.63	6.25	6.94
Mono-calcium phosphate	50.43	....	5.63	6.37	6.72
Di-calcium phosphate	39.34	....	5.56	6.02	6.98
Tri-calcium phosphate	36.14	....	5.66	6.10	6.96
Mono-ammonium phosphate	58.05	12.54	5.89	6.28	6.81
Ammoniated superphosphate (2.5%)	17.17	2.49	5.63	6.28	7.07
Ammoniated superphosphate (5%)	17.23	5.01	5.54	6.15	6.82
Rock phosphate†	33.74	....	5.57	6.01	6.90
Check plots	....	....	5.62	6.18	6.68
Average	....	....	5.63	6.18	6.86

*All materials, excepting superphosphate and rock phosphate, supplied through the cooperation of the DuPont Ammonia Corporation, Wilmington, Delaware.
†Tennessee brown rock, superfine.
‡Values given are averages of four plots for all phosphate treatments and of eight plots for checks. Soil samples taken after wheat harvest.

In Table 13 are listed the phosphates employed, together with their contents of total phosphoric acid (P_2O_5) and nitrogen. The final average soil reactions for the plots receiving each phosphate on the three ranges are also shown. The average total amount of limestone applied to the pH 6 range was 2162 pounds per acre, and to the pH 7 range, 10,524 pounds per acre.

The average yields and increases (over unphosphated checks on the same range) are shown for total grain and straw in Table 14 and for the grain alone in Table 15. The data for each individual reaction range were analyzed by the analysis of variance method of Fisher (3). From the standard errors thus obtained, the differences between the mean yields or increases required to give odds of 19 to 1 for significance were calculated and are shown in notes appended to Tables 14 and 15.

TABLE 14.—Yields and Increases of Wheat Grain and Straw in Phosphate-Reaction Experiment, 1933

Phosphate	Range 1		Range 2		Range 3		Average	
	pH 5.5		pH 6.0		pH 7.0			
	Yield	Increase	Yield	Increase	Yield	Increase	Yield	Increase
	Lb.	*Lb.*	*Lb.*	*Lb.*	*Lb.*	*Lb.*	*Lb.*	*Lb.*
20% superphosphate	4993	1618	5357	1868	4804	1997	5051	1828
Mono-calcium phosphate	4771	1396	4982	1493	5443	2636	5065	1842
Di-calcium phosphate	3957	582	4729	1240	4550	1743	4412	1185
Tri-calcium phosphate	4082	707	4061	572	2925	118	3689	466
Mono-ammonium phosphate	4425	1050	4907	1418	5050	2243	4794	1570
Ammoniated superphosphate, 2.5% N	4825	1450	4923	1450	4743	1936	4831	1612
Ammoniated superphosphate, 5.0% N	4486	1111	4193	704	3789	982	4156	932
Rock phosphate	3475	100	3493	4	2846	39	3271	48
Checks	3375	....	3489	....	2807	....	3227	....
Average	4265	....	4459	....	4106	....	4277	....

Note: Difference between yields or increases required to give odds of 19 to 1 for significance (calculated from standard errors obtained by Fisher's analysis of variance method).

Within ranges: Range 1, 956 pounds; Range 2, 550 pounds; Range 3, 505 pounds.

Between ranges: Ranges 1 and 2, 780 pounds; Ranges 2 and 3, 528 pounds; Ranges 1 and 3, 765 pounds.

TABLE 15.—Yields and Increases of Wheat Grain in Phosphate-Reaction Experiment, 1933

Phosphate	Range 1		Range 2		Range 3		Average	
	pH 5.5		pH 6.0		pH 7.0			
	Yield	Increase	Yield	Increase	Yield	Increase	Yield	Increase
	Bu.	*Bu.*	*Bu.*	*Bu.*	*Bu.*	*Bu.*	*Bu.*	*Bu.*
20% superphosphate	31.9	11.2	34.6	12.0	32.3	14.3	32.9	12.5
Mono-calcium phosphate	30.4	9.7	32.3	9.7	35.2	17.2	32.6	12.2
Di-calcium phosphate	26.2	5.5	30.3	7.7	30.9	12.9	29.1	8.7
Tri-calcium phosphate	27.1	6.4	27.1	4.5	21.2	3.2	25.1	4.7
Mono-ammonium phosphate	28.5	7.8	31.4	8.8	34.0	16.0	31.3	10.9
Ammoniated superphosphate, 2.5% N	31.2	10.5	31.5	8.9	32.3	14.3	31.7	11.2
Ammoniated superphosphate, 5.0% N	28.8	8.1	28.4	5.8	26.4	8.4	27.9	7.4
Rock phosphate	21.4	0.7	23.0	0.4	18.8	0.8	21.1	0.6
Checks	20.7	....	22.6	....	18.0	....	20.4	....
Average	27.4	....	29.0	....	27.7	....	28.0	....

Note: Difference between yields or increases required to give odds of 19 to 1 for significance (calculated from standard errors obtained by Fisher's analysis of variance method).

Within ranges: Range 1, 5.9 bu.; Range 2, 3.5 bu.; Range 3, 2.6 bu.

Between ranges: Ranges 1 and 2, 4.8 bu.; Ranges 2 and 3, 3.1 bu.; Ranges 1 and 3, 4.5 bu.

The efficiency of superphosphate, as measured by the increase in yield of either grain or grain and straw, tends to increase somewhat with increasing pH but the significance of the increase is doubtful. Mono-calcium phosphate, di-calcium phosphate, mono-ammonium phosphate, and ammoniated superphosphate (2.5 per cent nitrogen) all show the same tendency in greater degree, and, except for the last named phosphate, the differences between the increases at the lowest and highest reactions give high odds for significance. The change in reaction from pH 6 to pH 7 appears to have increased the efficiency of these materials more than the change from pH 5.5 to pH 6. Increasing pH seems to act in an opposite manner on the efficiency of tri-calcium phosphate, a progressive decrease in efficiency occurring with each increase in pH. In this case no single difference is highly significant, but, taken as a whole, the trend is probably significant. The more highly ammoniated superphosphate (5 per cent nitrogen) shows no significant change in efficiency with increasing pH. At all reactions it is less efficient than the ammoniated superphosphate containing only 2.5 per cent of nitrogen. Rock phosphate has failed to give significant increases in the yield of wheat at any reaction, indicating a low availability of this natural phosphate for the wheat crop. Even at the fairly acid reaction of pH 5.5, its effects are very meagre indeed.

The efficiency ratings of the different phosphates, calculated from the increases in yield at each reaction (taking superphosphate as 100), are shown in Table 16. The average rating for all three reactions is also shown. Of particular interest are: (a) the relatively high efficiencies of the two most acid materials, mono-calcium phosphate and mono-ammonium phosphate, at pH 7 and the relatively low efficiency of the same materials at pH 5.5 and pH 6; (b) the increase in relative efficiency of di-calcium phosphate and the decrease in relative efficiency of tri-calcium phosphate with increasing pH; (c) the marked differences in the relative efficiencies of the mono-, di-, and tri-calcium phosphates and of the two ammoniated superphosphates, particularly at the highest pH; and (d) the uniformly low relative efficiency of rock phosphate.

TABLE 16.—Efficiency Rating of Phosphates in Phosphate-Reaction Experiment

20% superphosphate taken as 100

Phosphate	pH 5.5		pH 6.0		pH 7.0		Average	
	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)
20% superphosphate	100	100	100	100	100	100	100	100
Mono-calcium phosphate	86	86	80	81	132	120	101	98
Di-calcium phosphate	36	49	66	64	87	90	65	70
Tri-calcium phosphate	44	57	31	38	6	23	25	38
Mono-ammonium phosphate	65	69	76	73	112	112	86	87
Ammoniated superphosphate, 2.5% N	90	94	78	74	97	100	88	90
Ammoniated superphosphate, 5.0% N	69	72	38	48	49	59	51	59
Rock phosphate	6	6	0	3	2	6	3	5

Note: Efficiency ratings in columns headed (1) are calculated from the increases in grain and straw; those in columns headed (2) are from the increases in grain alone.

Determinations of "available phosphorus" by Truog's method (21) were made on samples taken from the surface soil of all plots after the wheat crop was harvested. The average of the results for all plots of each treatment is given in Table 17.

TABLE 17.—Available Phosphorus by Truog's Method in Plot Soils of Phosphorus-Reaction Experiment

(Samples taken after harvest of wheat crop)

Phosphate	Available phosphorus per acre (2,000,000 lb. soil)		
	Range 1 pH 5.5	Range 2 pH 6	Range 3 pH 7
	Lb.	*Lb.*	*Lb.*
Superphosphate, 20%	49	55	47
Mono-calcium phosphate	54	49	50
Di-calcium phosphate	53	49	47
Tri-calcium phosphate	51	53	57
Mono-ammonium phosphate	52	48	46
Ammoniated superphosphate (2.5% N)	50	54	54
Ammoniated superphosphate (5% N)	51	57	49
Rock phosphate	58	61	62
Untreated checks	49	44	41

Although some allowance should doubtless be made for phosphorus removal by the wheat crop, it is notable that the increase in "available phosphorus" as measured by the method employed is small for all of the phosphates used and also that rock phosphate gives the largest apparent increase. The latter fact agrees with other observations of the authors that methods of measuring available phosphorus which are based upon dilute mineral acid extraction give values for rock phosphate – treated soils that are too high in comparison with the availabilities, as indicated by crop response. In general, from the data presented in Table 17, the possibility of measuring by such chemical methods the relative efficiency of the phosphorus in soils treated with normal amounts of various phosphates does not appear encouraging.[3]

GREENHOUSE PHOSPHATE EXPERIMENT

An experiment comparing the availability to Sudan grass in pot culture of 11 different phosphates was started in the spring of 1931. The test was one of a series conducted at different experiment stations in collaboration with

[3]Following the wheat crop of 1933 the land in this experiment was again planted to wheat after repeating the same fertilizer treatments made for the preceding crop. Yield data for the 1934 crop were not available until after the manuscript for this bulletin had been completed. Since, owing to the extreme drouth in the spring of 1934, the yields were abnormally low (averaging less than 5 bushels per acre on the check plots), the results were not believed to have sufficient reliability to warrant reporting them in detail. However, the efficiency ratings based upon the grain yields and comparable to those in Table 16 are presented below.

Efficiency Rating of Phosphates in Phosphate-Reaction Experiment, Based on Yields of Grain for the 1934 Wheat Crop

Phosphate	pH 5.5	pH 6.0	pH 7.0	Average
20% superphosphate	100	100	100	100
Mono-calcium phosphate	66	132	110	103
Di-calcium phosphate	46	98	101	82
Tri-calcium phosphate	50	88	40	59
Mono-ammonium phosphate	74	117	121	104
Ammoniated superphosphate, 2.5% N	58	128	92	93
Ammoniated superphosphate, 5.0% N	71	112	43	75
Rock phosphate	28	17	— 6	13

Although the order of the average ratings for the different phosphates in 1934 did not differ greatly from that of the preceding year, there is a notable increase in the ratings of all materials at pH 6. It is also notable that rock phosphate gave an efficiency of 28 per cent at pH 5.5 with a decrease to —6 in passing to pH 7.0. The efficiency of tri-calcium phosphate and of ammoniated superphosphate (5.0% N) is again low at pH 7.0 but all of the decrease occurs between pH 6.0 and pH 7.0; whereas in 1933 considerable decrease occurred in passing from pH 5.5 to pH 6.0.

Dr. W. H. Ross of the Bureau of Chemistry and Soils, U. S. Department of Agriculture. Their primary purpose was to determine the availability of ammoniated superphosphates of varying nitrogen content in comparison to such well known phosphates as superphosphate and rock phosphate and to certain pure phosphate salts known to be present in ammoniated superphosphates. Ross, Jacob, and Beeson (16) have published a report of these collaborative studies, including a partial report of the Ohio experiment which will be presented more fully here.

The soil used was a Canfield silt loam having an initial reaction of pH 5.1. Two series of pots were prepared. One hundred-mesh, high-calcium limestone was incorporated in amounts calculated to bring the reaction of one series to pH 6 and of the other to pH 7. The quantities of limestone added were equivalent, respectively, to 2700 and 7500 pounds per acre (2,000,000 pounds). The pots were of one-gallon capacity and had a surface area of 5.29×10^{-6} acres. The phosphates employed were supplied by Dr. Ross. They are listed and their chemical composition is shown in Table 18.

TABLE 18.—Composition of Phosphates Studied in Pot Experiment

No.*	Material†	Source of phosphate work	Content of phosphoric acid (P_2O_5)				Content of nitrogen
			Water soluble	Citrate insoluble	Available	Total	
			Pct.	Pct.	Pct.	Pct.	Pct.
A- 3	Superphosphate	Florida pebble	16.64	0.50	18.95	19.45	....
A- 5	Limed superphosphate	Florida pebble	0.62	10.77	6.53	17.30	....
A- 7	Ammoniated superphosphate.	Florida pebble	11.65	1.25	18.61	19.86	2.90
A- 8	Ammoniated superphosphate.	Florida pebble	11.27	4.26	15.90	20.16	5.36
A-13	Ammoniated superphosphate.	Florida pebble	0.40	11.65	7.69	19.34	7.12
B- 1	Mono-calcium phosphate	....	56.22	0.00	56.22	56.22	....
B- 2	Di-calcium phosphate	....	....	0.15	41.03	41.18	....
B- 3	Tri-calcium phosphate	....	....	20.13	21.24	41.37	....
B- 6	Mixture 4 parts tri-calcium and 1 part mono-ammonium phosphate	....	13.18	19.03	26.54	45.57	....
B- 7	Calcium hydroxy phosphate	....	....	33.95	6.06	40.01	....
B-14	Rock phosphate	Tennessee brown rock	....	31.88	1.98	33.86	....

*U. S. Bureau of Chemistry and Soils number.
†All materials and analyses supplied by Dr. W. H. Ross, U. S. Bureau of Chemistry and Soils.

Each phosphate was used at three rates, equivalent, respectively, to 30, 60, and 90 pounds of phosphoric acid (P_2O_5) per acre on the area basis. Additional rates equivalent to 15 and 135 pounds of phosphoric acid per acre were included in the case of superphosphate. Each treatment was represented by triplicate pots in each of the two reaction series. All pots, including the no phosphate checks, received the equivalent of 45 pounds each of nitrogen (N) and potash (K_2O), the former as sulfate of ammonia with proper allowance for any nitrogen contained in the phosphate and the latter as muriate of potash. All fertilizers were mixed with the soil before placing it in the pots.

On April 28 ten Sudan grass seeds were planted in each pot and after the seedlings appeared they were thinned to eight plants per pot. Six successive cuttings of the crop were made, the dates being June 19, July 7, July 28, August 17, September 16, and October 15. Each harvest of grass from a single plot was dried and weighed separately. The grass from the triplicate pots for a given treatment was then combined, pulverized, and analyzed for total phosphoric acid content.

TABLE 19.—Efficiency of Phosphates as Measured by Phosphoric Acid Removed by Sudan Grass in Pot Experiment

Material	Phosphoric acid (P_2O_5) added per A.	pH 6 Series						pH 7 Series					
		P_2O_5 removed in six cuttings, excess over checks	P_2O_5 recovery	Efficiency rating	P_2O_5 residual from fertilizer*	Available P_2O_5 excess over checks†	Av. final soil reaction	P_2O_5 removed in six cuttings, excess over checks	P_2O_5 recovery	Efficiency rating	P_2O_5 residual from fertilizer*	Available P_2O_5 excess over checks†	Av. final soil reaction
	Lb. per A.	*Lb. per A.*	*Pct.*		*Lb. per A.*	*Lb. per A.*	*pH*	*Lb. per A.*	*Pct.*		*Lb. per A.*	*Lb. per A.*	*pH*
Superphosphate	15	10.3	69		4.7	0	6.2	— 0.4	— 3		15.0	0	7.2
	30	16.8	56		13.2	2	6.1	6.4	21		23.6	8	7.1
	60	25.2	42		34.8	2	6.2	18.8	31		41.2	2	7.2
	90	38.5	43		51.5	2	6.1	24.8	28		65.2	8	7.1
	135	42.7	32		92.3	8	6.2	34.6	26		100.4	16	7.3
	Av.‡ 60	26.8	45	100	33.2	2		16.6	28	100	43.4	6	
Limed superphosphate	30	19.8	66		10.2	6	6.2	3.5	12		26.5	6	7.2
	60	27.5	46		32.5	6	6.4	7.0	12		53.0	14	7.3
	90	34.4	38		55.6	10	6.4	13.1	15		76.9	24	7.2
	Av. 60	27.2	45	101	32.8	7		7.8	13	47	52.2	15	
Ammoniated superphosphate 2.9% N	30	16.6	55		13.4	8	6.2	4.4	15		25.6	2	7.3
	60	21.3	36		38.7	16	6.2	13.5	22		46.5	16	7.3
	90	32.5	36		57.5	12	6.2	18.1	20		71.9	12	7.3
	Av. 60	23.5	39	87	36.5	12		12.0	20	72	48.0	10	
Ammoniated superphosphate 5.4% N	30	12.5	42		17.5	12	6.1	6.7	22		23.3	10	7.3
	60	26.2	44		33.8	14	6.1	7.8	13		52.2	12	7.4
	90	30.6	34		59.4	20	6.2	10.3	11		79.7	24	7.4
	Av. 60	23.1	38	86	36.9	15		8.3	14	50	51.7	15	
Ammoniated superphosphate 7.1% N	30	14.0	47		16.0	6	6.2	— 0.7	— 2		30.0	4	7.5
	60	18.4	31		41.6	8	6.2	6.3	10		53.7	16	7.4
	90	29.8	33		60.2	22	6.2	5.8	6		84.2	24	7.2
	Av. 60	20.7	35	77	39.3	12		3.8	6	23	56.2	15	
Mono-calcium phosphate	30	14.2	47		15.8	4	6.1	5.3	18		24.7	6	7.3
	60	27.5	46		32.5	8	6.2	17.1	28		42.9	18	7.3
	90	36.7	41		53.3	8	6.2	20.3	23		69.7	16	7.4
	Av. 60	26.2	44	97	33.8	7		14.3	24	86	45.7	13	

*Difference between P_2O_5 added and P_2O_5 recovered in excess over checks. †At end of experiment. Determined by method of Truog (21).
‡Averages for superphosphate series are for 30, 60, and 90 pounds P_2O_5 applications.

TABLE 19.—Efficiency of Phosphates as Measured by Phosphoric Acid Removed by Sudan Grass in Pot Experiment—Continued

Material	Phosphoric acid (P_2O_5) added per A.	pH 6 Series						pH 7 Series					
		P_2O_5 removed in six cuttings, excess over checks	P_2O_5 recovery	Efficiency rating	P_2O_5 residual from fertilizer*	Available P_2O_5 excess over checks†	Av. final soil reaction	P_2O_5 removed in six cuttings, excess over checks	P_2O_5 recovery	Efficiency rating	P_2O_5 residual from fertilizer*	Available P_2O_5 excess over checks†	Av. final soil reaction
	Lb. per A.	*Lb. per A.*	*Pct.*		*Lb. per A.*	*Lb. per A.*	*pH*	*Lb. per A.*	*Pct.*		*Lb. per A.*	*Lb. per A.*	*pH*
Di-calcium phosphate	30	16.4	55		13.6	4	6.2	5.4	18		24.6	4	7.4
	60	22.0	37		38.0	4	6.3	14.5	24		45.5	12	7.3
	90	32.0	36		58.0	8	6.3	22.7	25		67.3	12	7.2
	Av. 60	23.5	39	87	36.5	5		14.2	24	85	45.8	9	
Tri-calcium phosphate	30	16.7	56		13.3	8	6.1	1.4	5		28.6	10	7.3
	60	25.6	43		34.4	2	6.2	4.7	8		55.3	18	7.3
	90	37.0	41		53.0	10	6.2	11.3	12		78.7	28	7.3
	Av. 60	26.4	44	98	33.6	7		5.6	9	35	54.4	19	
Tri-calcium phosphate and mono-ammonium phosphate	30	16.0	53		14.0	2	6.3	2.6	9		27.4	10	7.1
	60	25.0	42		35.0	8	6.2	7.1	12		52.9	22	7.4
	90	35.9	40		54.1	16	6.2	8.9	10		81.1	26	7.4
	Av. 60	25.6	43	96	34.4	9		6.2	10	37	53.8	19	
Calcium hydroxy phosphate	30	11.4	38		18.6	12	6.1	−1.0	−3		30.0	18	7.5
	60	17.1	29		42.9	22	6.2	0.3	0		59.7	32	7.4
	90	20.3	23		69.7	32	6.3	−5.3	−6		90.0	46	7.3
	Av. 60	16.3	27	61	43.7	22		−2.0	−3	−12	60.0	32	
Rock phosphate	30	8.2	27		21.8	20	6.1	−8.5	−28		30.0	16	7.3
	60	7.7	13		52.3	36	6.1	−6.4	−11		60.0	36	7.3
	90	7.5	8		82.5	48	6.2	−4.5	−5		90.0	44	7.2
	Av. 60	7.8	13	29	52.2	38		−6.4	−11	−39	60.0	32	
Average checks	....	32.3	....	....	....	16	6.0	55.8	....	....	....	20	7.4

Note: Differences required to give odds for significance of 19 to 1 and of 99 to 1, estimated from general standard error obtained by Fisher's analysis of variance method.

	Odds for significance 19 to 1	Odds for significance 99 to 1
Between phosphoric acid removals for individual rates of addition for the same or different materials	1.15 lb.	1.63 lb.
Between the average removals of different materials	0.60 lb.	0.81 lb.
Between efficiency ratings, pH 6 series	2.2	3.0
Between efficiency ratings, pH 7 series	3.6	4.9

In the case of the first cutting the variations in rate and availability of the phosphoric acid added were reflected in the yields of grass obtained and also in the total amounts of phosphoric acid removed but not markedly in the percentages of phosphoric acid in the crop. In the second and third cuttings the yields did not reflect either the quantity or availability of the phosphates applied, the tendency being for the higher yields to be produced from the smaller phosphoric acid additions and the less available phosphates. However, there were notable differences in the percentages of phosphoric acid contained, and the total phosphoric acid removals were in substantially the same order as in the first cutting. This was interpreted as indicating a deficiency of either nitrogen or potash or both after the first cutting. Accordingly, sufficient potassium nitrate and urea to equal the initial basic treatment were added in solution after making the third cutting, again after making the fourth cutting, and before and twice during the growth of the sixth cutting. The relation of yield and total phosphoric acid removal to the rate of phosphoric acid addition for the pots receiving superphosphate in the pH 6 series is shown graphically in Figure 10. It appears that only in the case of the first and sixth cuttings are the yields of grass positively correlated with the rate of phosphate addition; whereas the total phosphoric acid removal shows throughout a close relation to the amount of phosphate added, excepting for the heaviest rate in certain cuttings. It seems evident that the removal of phosphoric acid should be a much better measure of availability in the present study than the yields of grass harvested.

After the sixth cutting the soil was removed from the pots, and, after separating the roots, samples of the thoroughly mixed soil were taken for determinations of pH and of available phosphoric acid by the method of Truog (1c).

In Table 19 are presented summary data showing (a) the total phosphoric acid removed by six cuttings in excess of the checks for each rate of addition and the average of these for each phosphate; (b) efficiency ratings for all materials based upon the average removal for the three rates of addition of each phosphate, taking superphosphate as 100; (c) the percentage of the added phosphoric acid removed; (d) the amount of phosphoric acid residual from the treatment; (e) the available phosphoric acid in the soil by the Truog method; and (f) the final soil reaction.

The data for the entire experiment were analyzed statistically by Fisher's (3) analysis of variance method, employing as the basic data the average phosphoric acid removals for each cutting at each rate of phosphate addition for each material at each reaction. Table 20 presents the summary of this analysis. High significance is indicated for variance due to material, rate of addition, cutting, reaction, and for all of the interactions listed. At the bottom of Table 19 is shown the magnitude of the differences, estimated from the general standard error, required to give odds of 19 to 1 and of 99 to 1 for significance between the phosphoric acid removals for individual rates of addition for the same or different materials at a given reaction, between the average removals of different materials at a given reaction, and between the efficiency ratings.

Reference to Table 19 shows that for the pH 6 series the average actual reaction of the unphosphated soil was 6.0 and of the phosphated soils pH 6.1 to pH 6.4. Similarly, the average reaction of the unphosphated soil in the pH 7 series was pH 7.4, the phosphated soils ranging from pH 7.1 to pH 7.5.

TABLE 20.—Summary of Fisher's Analysis of Variance for the Data Obtained in the Greenhouse Phosphate Experiment

Cause of variation	Degrees of freedom	Value of F†	
		Actual	For 1% significance (Approx.)
Amount of phosphoric acid	2	176.76	3.04
Kind of phosphate	10	47.54	1.85
Cutting	5	122.30	2.26
Soil reaction	1	787.87	3.89
Interactions:			
Amount of phosphoric acid and kind of phosphate	20	3.91	1.50
Amount of phosphoric acid and cutting	10	4.85	1.85
Amount of phosphoric acid and soil reaction	2	14.01	3.04
Kind of phosphate and cutting	50	2.62	1.50
Kind of phosphate and soil reaction	10	5.08	1.85
Cutting and soil reaction	5	21.60	2.26
Error*	280	1.00	....

*$\sigma\ x_{error} = 0.8928$ lb. per acre.
†Notation of Snedecor (20).

The average phosphoric acid removal in the unphosphated pots was notably higher in the pH 7 series than in the pH 6 series, the former being 72.6 per cent higher than the latter. It is probable that the greater removal at the higher reaction was largely the result of a higher availability of the native soil phosphorus at this reaction. It is true that the yield of Sudan grass was higher on the unphosphated soil in the pH 7 series than in the pH 6 series, which may or may not have resulted from an increased availability of soil phosphorus and which would account for some of the increased removal. However, the yield of grass in the pH 7 series exceeded that of the pH 6 series by only 22.2 per cent in comparison to a 72.6 per cent greater removal of phosphoric acid. Moreover, the average phosphoric acid content of the grass harvested from the unphosphated pots of the pH 6 series was 0.245 per cent compared to 0.346 per cent for the pH 7 series.

TABLE 21.—Average Recovery of Phosphoric Acid in the pH 7 Series as Per Cent of the Recovery in the pH 6 Series

Material	Recovery of P_2O_5 in pH 7 series, as per cent of pH 6 series	Material	Recovery of P_2O_5 in pH 7 series, as per cent of pH 6 series
Superphosphate	62.0	Mono-calcium phosphate	54.6
Limed superphosphate	28.7	Di-calcium phosphate	60.4
Ammoniated superphosphate, 2.9% N	51.1	Tri-calcium phosphate	21.2
Ammoniated superphosphate, 5.4% N	35.9	Tri-calcium phosphate and mono-ammonium phosphate	24.4
Ammoniated superphosphate, 7.1% N	18.3	Calcium hydroxy phosphate	—12.3
		Rock phosphate	—82.0
		Soil alone	172.6

The recoveries of phosphoric acid from all phosphates at all rates of addition were notably less in the pH 7 series than in the pH 6 series. The magnitude of the differences is indicated in Table 21, which shows the average recovery of phosphoric acid for each phosphate in the pH 7 series stated as per cent of the corresponding recovery in the pH 6 series.

For those materials which carry their phosphoric acid chiefly as the mono- or di-calcium phosphates—i. e., superphosphate, ammoniated superphosphate (2.9 per cent nitrogen), mono-calcium phosphate, and di-calcium phosphate—the recovery in the pH 7 series ranges between 51.1 per cent and 62.0 per cent of the recovery in the pH 6 series. It is conceivable that this reduced removal resulted from the increased availability of the native soil phosphorus rather than from an actual reduction in the availability of the added phosphates. That the latter possibly was also involved is indicated by the following facts. The removal of phosphoric acid on the untreated pots of the pH 7 series was within one pound per acre of the average removal of the four phosphates mentioned above when used to supply 60 pounds of phosphoric acid in the pH 6 series. With these same phosphates, the addition of the third increment of 30 pounds of phosphoric acid in the pH 6 series increased the average removal by 10.9 pounds per acre; whereas the first 30-pound increment of phosphoric acid in the pH 7 series gave an increase in the average removal of only 5.4 pounds per acre. Further evidence is found in the fact that the second increment of 30 pounds of phosphoric acid for these same phosphates in the pH 7 series increased the average recovery by 10.6 pounds of phosphoric acid, nearly double the recovery from the first increment—a result that might be interpreted as being due to a decrease in the soil's power to fix added phosphoric acid with increasing addition and progressive saturation of its absorptive capacity.

In Table 21 it is notable that the recovery of phosphoric acid in the pH 7 series from those phosphates carrying all or a considerable part of their phosphoric acid in the form of tri-calcium phosphate (i. e., the ammoniated superphosphates containing 5.4 and 7.1 per cent of nitrogen, tri-calcium phosphate, and the mixture of tri-calcium phosphate and mono-ammonium phosphate) ranged from 18.3 to 35.9 per cent of the corresponding recoveries in the pH 6 series. The availability of these materials is thus seen to be depressed much more at the more alkaline reaction than that of the materials mentioned in the preceding paragraph.

The average recoveries of phosphoric acid for the rock phosphate and calcium hydroxy phosphate pots in the pH 7 series were significantly less than the recoveries for the unphosphated pots, leading to negative values in Table 21. That these negative recoveries resulted from a detrimental influence of these materials on yield and not from an actual depression of the availability of the phosphoric acid present below that of the unphosphated soil is indicated by the fact that for each rate of addition of each phosphate the total yield of crop harvested was significantly below the yield of the unphosphated pots whereas the percentage of phosphoric acid in the crop harvested was in all cases slightly higher than in the crop from the unphosphated pots. The depression in yield was more serious in the case of rock phosphate, and it is possible that the fluorine contained may have exerted a deleterious effect on the crop.

From the efficiency ratings in Table 19 it is observed that in the pH 6 series all phosphates, excepting rock phosphate, calcium hydroxy phosphate, and ammoniated superphosphate (7.1 per cent nitrogen), fall within 15 per cent of the availability of superphosphate; whereas in the pH 7 series only the mono- and di-calcium phosphates fall within this range. In the latter series the ammoniated superphosphates show rapidly decreasing availabilities with increasing nitrogen content. Limed superphosphate is equal to superphosphate in efficiency in the pH 6 series but is only about one-half as efficient in the pH 7 series. Tri-calcium phosphate and the mixture of tri-calcium phosphate and mono-ammonium phosphate are both nearly equal to superphosphate in efficiency in the pH 6 series but only a little more than one-third as efficient as superphosphate in the pH 7 series. The apparent negative efficiencies of calcium hydroxy phosphate and rock phosphate in the pH 7 series have already received comment.

The results shown in Table 19 for "available" phosphoric acid, determined by the Truog method on the pot soils at the end of the experiment, appear to indicate a much more complete fixation of the phosphoric acid residual from superphosphate and the other more readily available forms than from the relatively unavailable materials—rock phosphate and calcium hydroxy phosphate. However, as was pointed out in connection with the previous field experiment, the chemical method is probably poorly adapted to showing the relative availability of added phosphates to the crop. Thus, in Table 19, it appears from a comparison of the results the pots receiving 90 pounds of phosphoric acid as superphosphate in the pH 6 series with the corresponding pots receiving rock phosphate that the available phosphoric acid in the soil of the former exceeds that in the unphosphated checks by only 2 pounds per acre. Moreover, the corresponding rock phosphate-treated soils gave 48 pounds per acre of soluble phosphoric acid in excess of the check. This difference is in distinct contrast to the phosphoric acid recovered by the crop in the two cases, the total recoveries from the superphosphate and rock phosphate pots standing in the ratio of about 5 to 1 and the recoveries in the last cutting in the ratio of about 3 to 1. The available phosphoric acid in the check soils of the pH 7 series exceeds that of the check soil of the pH 6 series, which is in line with the greater phosphoric acid removal by the crop in the more alkaline series. On the other hand, in most instances a larger part of the phosphoric acid residual from the fertilizer treatments shows up as available at pH 7 than at pH 6; whereas the availability to the crop was less for all materials at the former reaction, with some materials notably so. As a whole, even when allowance is made for the fact that the chemical determinations were not made until the end of the experiment and, hence, were concerned only with residual phosphates, it seems evident that there is little agreement between chemical solubility with the method employed and availability as measured by phosphate assimilation by the crop.

GENERAL DISCUSSION

An attempt will be made in this section to bring together the results of the experiments previously discussed and to interpret them collectively as they apply to a few of the more important questions of phosphate availability as it is affected by soil reaction. From what has preceded, the complexity of the problem is evident. In employing crop response as the measure of availability it is desirable, but not always possible, to differentiate between the effects of soil reaction upon the availability of native and applied phosphates. Moreover, crops differ in their capacity to utilize phosphoric acid in different forms, and changes in soil reaction do not affect all crops alike in their ability to use the different phosphates. Some phosphates have a neutralizing effect on the soil and this tends to mask the phosphate effect, particularly on acid-sensitive crops on acid soils. No consideration has been given to the time of applying either the phosphates or lime in relation to the growth period of the crop. Recent work of Scarseth and Tidmore (17) indicates that both may be

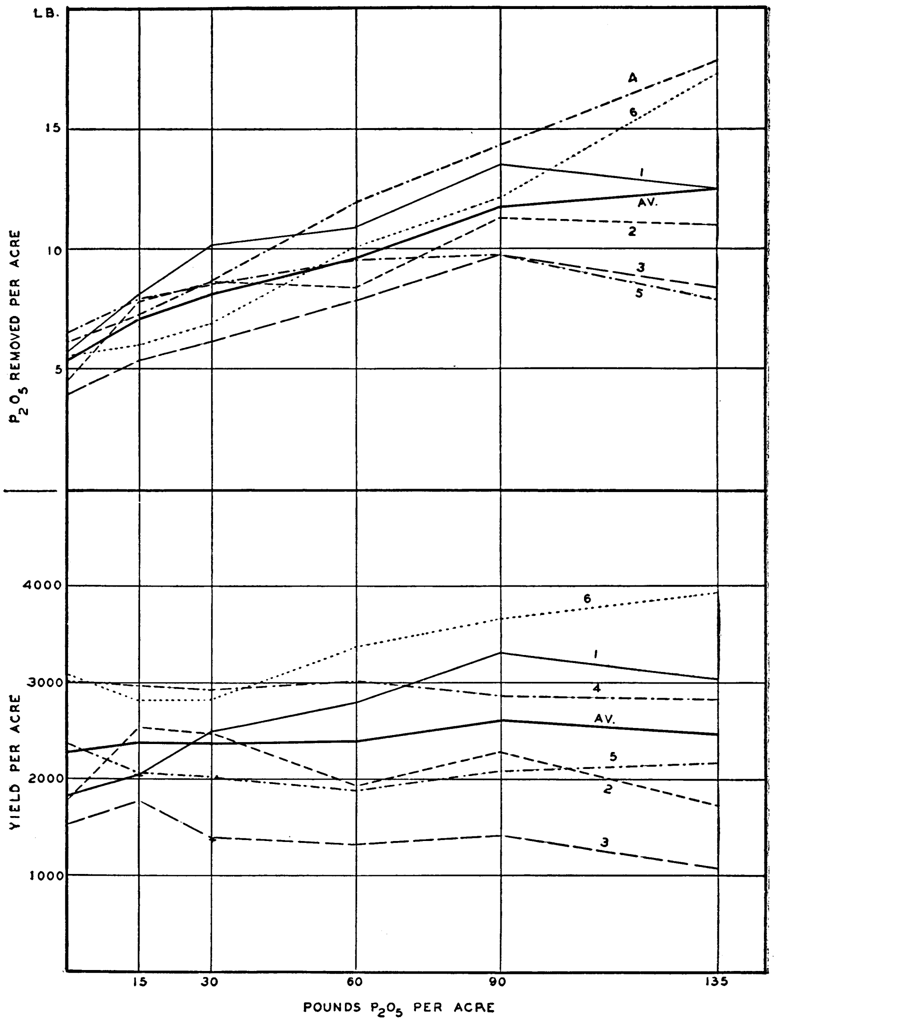

Fig. 10.—Yield of Sudan grass and removal of phosphoric acid (P_2O_5) for individual cuttings with increasing additions of P_2O_5 as superphosphate, pH 6 series

important. They found with superphosphate and other readily available phosphates a progressive fixation and corresponding decrease in availability with increasing time after application and also a notable depression in the availability of added phosphates when lime was applied at the same time. However, there was a progressive lessening of this effect as the time of the lime application was advanced ahead of the phosphate application. These effects may have been involved in the experiments under consideration but the latter were not planned to evaluate them. All of the experiments reported were conducted on either Wooster or Canfield silt loams, two soils practically identical in their surface horizons. Scarseth and Tidmore (18) and Gile (7) have reported notable differences between soils in their capacities to render added phosphates unavailable; hence, the results of the present studies cannot, without further proof, be assumed to be universally applicable.

THE EFFECT OF SOIL REACTION UPON THE AVAILABILITY OF NATIVE SOIL PHOSPHORUS AND UPON THE RESPONSE TO SUPERPHOSPHATE

Practically, the farmer is interested in knowing what combination of soil reaction and phosphate supply will produce the largest economic returns. Involved in this question are the effects of soil reaction upon the availability of native soil phosphorus and upon the availability of phosphorus supplied in fertilizers, as well as the comparative cost of lime and phosphates. Among the experiments herein reported, only the pot experiment affords any direct evidence on the effect of reaction upon the availability of native soil phosphorus. In this experiment phosphorus removal by Sudan grass is the criterion of availability employed, and the relatively high removal from the unphosphated pots at pH 7.4 compared to that at pH 6.0 points to a considerable increase in availability of the native phosphorus in this soil when its reaction is increased from pH 6.0 to pH 7.4. In the other experiments yield response is assumed to measure phosphate availability. Its use does not permit a sure separation of the effects of reaction on native and applied phosphates. High phosphate fixing power of the soil should make for low availability of native phosphorus. This, in turn, should lead to a relatively great need for phosphorus and a correspondingly high response to phosphate fertilizers. On the other hand, the same high fixing power should lead to the rapid fixation of added phosphates, and, while the immediate results of such additions might be large, the later response might well be below that from similar additions to a soil with less fixing power. It is conceivable that, on soils of high fixing power, the effect of phosphate applications on the immediate crop might be a relatively high response whereas that on subsequent crops might be relatively low when both are compared to the results on soils of low fixing power. The extent of contact of soil and fertilizer also would doubtless be a factor. Localized placement with minimum contact might be expected to give high response and broadcast applications with extensive contact, low response.

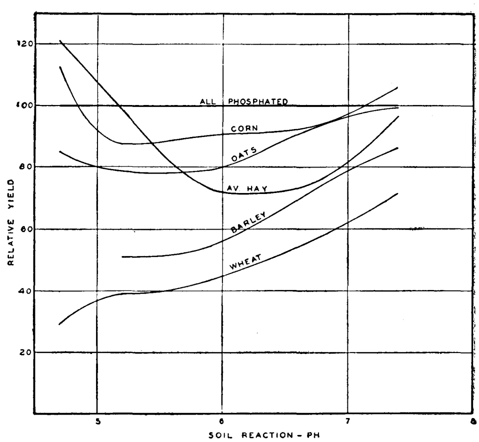

Fig. 11.—Unphosphated yields in Legume-Reaction Experiment. Relative basis, phosphated yields taken as 100.

In Figure 11 are presented graphically the relative yields of the crops grown in the Legume-Reaction Experiment plotted against the actual average pH values of the soil. The phosphated yield at each reaction is taken as 100 and the unphosphated yield is expressed as a percentage of this. The deviations of the unphosphated yield curves from the 100 per cent line represent the response to phosphate. It will be recalled that in this experiment superphosphate is applied only to the grain crops. The response of the hay crops is thus a residual effect. From the graph it is noted that the grain crops all show a marked decrease in phosphate response as the pH increases from 5.9 to 7.4. The curve representing the average unphosphated yield of all seven hay crops shows the same tendency but the most rapid decrease in response occurs between pH 6.8 and pH 7.4. It is interesting that at the latter reaction the unphosphated yields of corn, oats, and hay are approximately equal to the phosphated yields. Of even greater significance is the fact that the absolute unphosphated yields of corn and oats and of most of the hay crops at pH 7.4 are close to the maximum yields obtained in the experiment. This is believed to indicate that the decreasing response observed as the reaction is increased above pH 5.9 is primarily the result of an increase in the availability of the native soil phosphorus with a corresponding decrease in the need for fertilizer additions.

With corn and oats a decrease in phosphate response occurs from pH 5.2 to pH 4.7. With barley no yield whatever is obtained at pH 4.7; whereas with wheat the highest response is obtained at the most acid reaction. With the hay crops, the average response to superphosphate decreases as the acidity is increased below pH 5.9. As previously noted, this decreased response at low pH may result either from an increased availability of native phosphorus or an increased fixation of the phosphorus supplied as superphosphates. Both factors may be involved.

In Figure 12 is shown graphically the dilute organic acid-soluble phosphorus[4] in soil samples taken in the fall of 1933 following red clover hay. It is observed that Curve (2), showing the solubility for the unphosphated soils at a constant pH of 3.35, correlates well with the curves for relative unphosphated yields (Fig. 11) in indicating a minimum availability of native soil phosphorus between pH 5 and pH 6. There is an increasing availability at both more acid and more alkaline reactions. In general, this agrees with the results of Gaarder (5) who found the concentration of the phosphate ion in the presence of a mixture of calcium, magnesium, iron, aluminum, and manganese ions to be at a minimum around pH 5 to pH 6.5, with maximum solubility near pH 4.5 and an increasing solubility from pH 6.5 to pH 8.0. The effect of soil reaction upon the fixation of the added superphosphate may also have been a factor in the results obtained in the Legume-Reaction Experiment. A comparison of the phosphated (1) with the unphosphated (2) curves in Figure 10 indicates largest fixation of applied phosphorus in the regions of least crop response. However, the fact that both a grain and a hay crop had been grown between the time of the last superphosphate addition and the time of sampling these soils renders doubtful the interpretation of these data. Gile (7) found

[4]The methods employed in the solubility determinations were modifications of a procedure being successfully used in the authors' laboratory for measuring available soil phosphorus. For the solubility determination at constant pH enough of a stock solution containing 7 gm. malic acid, 7 gm. citric acid, and 2.5 gm. oxalic acid per liter was added with vigorous stirring to a 50 gm. sample of soil to bring the reaction of the suspension to pH 3.35, measured with an antimony electrode. The suspension was diluted with water to 100 c. c. volume and then boiled 2 minutes, filtered at once, and phosphorus determined in the filtrate colorimetrically by a modification of the ceruleo-molybdate procedure. In the series of "unadjusted" determinations (Curve 3, Fig. 12) the same method was employed excepting that a constant amount, 10 c. c., of the stock acid solution was added to each sample.

that soils whose colloids contained relatively large amounts of silica in proportion to oxides of iron and aluminum (a high silica-sesquioxide ratio) commonly enhanced the availability of superphosphate in sand culture. The opposite was true for soils whose colloids were relatively low in silica and high in iron and aluminum. Although data are not available on the composition of the Wooster and Canfield colloids, their ratio of silica to sesquioxides is probably between 2.5 and 3.0, an intermediate value which might be expected to result in a rather slight or indifferent effect on the availability of superphosphates.

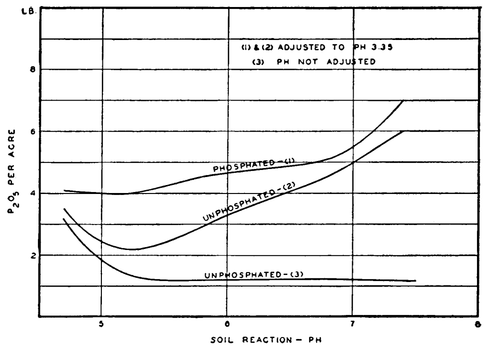

Fig. 12.—Organic acid soluble phosphoric acid (P_2O_5) in plot soils of Legume-Reaction Experiment

The results of the Legume-Reaction Experiment suggest that by maintaining this soil at a reaction of approximately pH 7.5 good yields of crops may be obtained with a minimum investment in phosphate fertilizers. The Five-year Rotation and Manure Experiments also tend to support this idea. Plot 9 in the Five-year Rotation Experiment has received 260 pounds of muriate of potash and 480 pounds of nitrate of soda in each of the eight rotations since 1894. No phosphorus whatever has been applied and all crops have been removed from the land. It would appear that ideal conditions should have obtained on this plot for the development of a serious shortage of available phosphorus. In Figure 13 are shown the yield trends of corn and wheat, as indicated by straight line regressions for the two ends of this plot since liming was begun on the west end in 1900. A notable decline in yield is observed for both corn and wheat on the unlimed soil. On the limed soil however, the yield of wheat has remained nearly constant and the yield of corn has actually increased materially despite the absence of any phosphorus addition. It will be recalled that the reaction of the limed soil was initially around pH 5 and

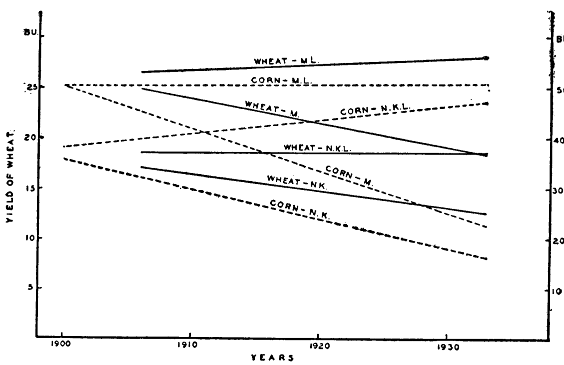

Fig. 13.—Straight line regressions of yields of corn and wheat on time for limed and unlimed ends of Plot 9 (KN) and Plot 20 (manure) of the Five-year Rotation Fertility Experiment.

has gradually been increased by repeated limings to approximately pH 7.5 at present. That the availability of the native soil phosphorus has increased sufficiently with increasing pH to compensate for the depleting effects of continued crop removal is suggested as the explanation of the stability of the yields on this soil. In Figure 13 are also shown yield regression lines for corn and wheat on Plot 20, receiving in each rotation 4 tons of yard manure on both corn and wheat. Although the estimated removal of phosphorus in the crops grown on the limed end of the plot has been more than twice that carried in the manure, the yields of both corn and wheat have been maintained at a very satisfactory level. In contrast, the yields of both crops have declined on the unlimed ends, notably so in the case of corn. Although the indirect effect of the changing clover yields (improving on the limed soil and approaching nothing on the unlimed) upon the yield of the grain crops was doubtless a factor in the results noted on both plots, it is evident that with repeated liming and the regular growing of clover on this soil the supply of available soil phosphorus has been sufficient to maintain a constant and even slightly increasing level of grain yields during the 40-year period.

The topography of the area devoted to this experiment is sufficiently rolling so that moderate sheet erosion has occurred. No measure of the amount of surface soil removed in the 40-year period is available although it is certainly no greater than what has occurred on the same soil type on practical farms of the region. Doubtless, erosion has tended to renew the phosphorus content of the surface soil by gradual incorporation of subsoil with the plow layer. However, this influence should have been as important on the unlimed as on the limed land of the experiment. Hence, the diverging yield trends on the limed and unlimed ends of the unphosphated plots probably remain a legitimate criterion of the effect of diverging pH upon the availability of native soil phosphorus.

Evidence supporting the idea that repeated liming of this naturally acid soil results in more soil phosphorus becoming available is also supplied by the Barnyard Manure Experiment. Here there has been a gradual increase in the yields of all crops from 1897 to 1933 on the plots receiving either stall or yard manure supplemented with superphosphate. On the plots receiving similar manure treatments without superphosphate the yields have increased even more rapidly, cutting down the apparent response to superphosphate and indicating an improved supply of available native phosphorus.

The literature contains many references to other work showing the effect of lime in increasing the availability of phosphorus in acid soils—Truog and Parker (22), Parker and Tidmore (14), Simon (19), Weiser (24), and others. According to the ideas of Ford (4) and Heck (8) the explanation is found in the tendency for the phosphorus in acid soils to be held in relatively insoluble combinations with hydrated oxides of iron and aluminum. With increasing pH and calcium concentration following liming these compounds become unstable and break down, the phosphorus combining with calcium to form calcium phosphates of relatively high availability. In the use of tests for available phosphorus in soils that depend upon solubility in dilute acids it is common experience to find high availability indicated in limed soils or naturally calcareous soils. Many thousands of such tests on Ohio soils have revealed this tendency unmistakably. On the other hand, there is evidence that with increased lime additions a point may be reached where phosphorus again becomes less available. Breazeale and McGeorge (1) have called attention to the apparent lack of available phosphorus in alkaline calcareous soils of Arizona, partly explained by the inability of crops growing on such soils to maintain the reaction at the root-soil interface below pH 7.5, above which intake of neither phosphate nor nitrate can take place, and partly by the occurrence of phosphorus in such soils in the form of a highly insoluble carbonate-phosphate compound in which 1 mol of calcium carbonate is combined with 3 mols of tri-calcium phosphate (13). Their experiments indicate that the most insoluble reaction range for phosphate lies between pH 8.0 and pH 8.5. It may be pointed out that only occasional soils are found in Ohio which show reactions within this range. With few exceptions such soils are either subsoils or surface soils low in organic matter which contain considerable free calcium carbonate. None of the soils considered in this bulletin show reactions as high as pH 8. It is entirely possible, however, that if liming had been carried to this point a reduced availability of soil phosphorus would have resulted. Gaarder's (5) curves indicate a reduced solubility of phosphate above pH 8.0 in the presence of the ordinary soil bases and it is not unlikely that the occasional unfavorable effects observed immediately after an application of lime [See Karraker (10)] are a manifestation of the effects of solid phase calcium carbonate in reducing the availability of soil phosphates.

THE EFFECT OF SOIL REACTION UPON THE AVAILABILITY OF PHOSPHATE FERTILIZERS

Superphosphates.—None of the experiments herein reported supply satisfactory direct evidence of the effect of soil reaction upon the availability of ordinary superphosphates. Several instances have been noted where the yield response to superphosphate has decreased with increasing alkalinity up to about pH 7.5, and in the Legume-Reaction Experiment several crops indicate a decreased yield response at the most acid reaction, pH about 4.7. That these effects probably reflect in part an increased availability of native soil phosphorus and hence a lessened need for phosphate additions in these regions of low response has been pointed out in the foregoing discussion. Whether an increased fixation of phosphorus applied as superphosphate was also involved cannot be stated with certainty. In the discussion of the Greenhouse Pot Experiment some evidence was presented which indicated an actual reduction in the availability of superphosphate in the pH 7 series as compared to the pH 6 series. The nature of this evidence was not conclusive however. Work of other investigators indicates that soil reaction may affect the availability of applied superphosphates. Gile (7) has studied the effect of a number of soils upon the efficiency of superphosphate at varying pH and reports, "It seems certain that the maximum availability of superphosphate in the presence of these soils is in the acid range, somewhere about pH 4.5 to 5.0. The minimum availability seems to be somewhere around neutrality, pH 6.5 to 7.5, and there is a suggestion of a small increase in availability in the distinctly alkaline range. Scarseth and Tidmore (17) studied the effect of time of applying calcium carbonates, added to an acid Vaiden clay soil in an amount calculated to bring its reaction to pH 6.5, upon the availability of a number of phosphates, including superphosphate, as measured by Truog's method (21) and the yield of sorghum in pots. The authors state that "calcium carbonate greatly decreased the availability of readily soluble phosphates and the crop yield when applied immediately before planting to the acid clay soil, whereas after equilibrium was established and $CaCO_3$ was no longer present in the soil the availability of the phosphates increased as shown by the yield of sorghum." It appears from their work that applications of lime made coincidently with superphosphate may have a depressing effect upon the availability of the latter so long as free calcium carbonate remains in the soil. In other work by the same authors (18) both mono- and di-calcium phosphate (the essential ingredients of superphosphates) were added to four colloids ranging in silica-sesquioxide ratio from 1.57 to 3.81 and in calcium saturation from 0 to 200 per cent. Recoverability of the applied phosphate in 0.05/N and 0.1/N H_2SO_4 was determined. There was no consistent evidence that availability of phosphorus as measured by this method was reduced by increasing calcium saturation up to 100 per cent, and this point is probably seldom exceeded in field soils. It is evident that further study is needed to establish definitely the effect of soil reaction and liming upon the availability of superphosphates.

In the following discussion other phosphate fertilizers will be considered by comparing them with superphosphate. Although the true relation of soil reaction to the availability of the latter has not been shown, a comparison of other materials with superphosphate, the most widely used phosphate fertilizer in practice, should be of value.

Steamed bone meal.—Among the experiments considered, bone meal has been used only in the Five-year Rotation Experiment where it is compared with superphosphate and basic slag, all used to supply equal amounts of phosphoric acid and supplemented with muriate of potash and nitrate of soda. Efficiency ratings for bone meal, compared to superphosphate taken as 100, are shown for the different crops and for different periods in Table 22. These efficiencies are calculated from the increases for phosphorus over potash and nitrogen.

TABLE 22.—Efficiency Ratings for Phosphoric Acid in Steamed Bone Meal, Superphosphate=100

Five-year Rotation Experiment

Crop	Unlimed			Limed		
	First 5-yr. period	Last 5-yr. period	Entire period*	First 5-yr. period	Last 5-yr. period	Entire period*
Corn	81	78	70	85	−47	46
Oats	75	75	75	76	21	33
Wheat	75	96	86	80	20	45
Clover	112	104	100	124	30	90
Timothy	81	84	60	101	96	115
Average	85	87	78	93	24	66
Av. grain crops	77	83	77	80	−2	41

*1900-1933.

The data indicate that for the grain crops bone meal has been approximately 80 per cent as efficient as superphosphate on this soil when unlimed and for the 5-year period following the first application of lime. With repeated liming its efficiency for the same crops has dropped markedly, and, for the last 5-year period, with the soil reaction about pH 7.5, its average efficiency is practically zero. The residual effect of bone meal on the clover crop has been fully equal to that of superphosphate throughout the experiment on the unlimed land. However, on the limed land the efficiency of bone meal has dropped to only 30 per cent of that of superphosphate in the last 5-year period. The results for the timothy crop indicate a greater residual effect of bone meal on the limed than on the unlimed land. This is believed to reflect a greater residue of phosphate on the limed land due to its less complete utilization by the preceding wheat and clover crop, rather than a higher efficiency of bone meal at the more alkaline reaction.

Basic slag.—In Table 23 are presented the efficiency ratings for basic slag comparable to those shown for bone meal in Table 22.

TABLE 23.—Efficiency Ratings for Phosphoric Acid in Basic Slag. Superphosphate = 100

Five-year Rotation Experiment

Crop	Unlimed			Limed		
	First 5-yr. period	Last 5-yr. period	Entire period*	First 5-yr. period	Last 5-yr. period	Entire period*
Corn	74	75	87	76	−45	51
Oats	52	84	74	53	68	50
Wheat	97	90	99	67	76	78
Clover	89	144	138	67	85	92
Timothy	88	149	119	68	125	99
Average	80	108	103	66	62	74
Av. of grain crops	74	83	87	65	33	60

*1900-1933.

It is evident that on the unlimed land basic slag has been approximately 85 per cent as efficient as superphosphate for the grain crops, ranking a little higher than bone meal. On the limed land its efficiency in the last 5-year period has dropped below zero for corn but is about 80 per cent as great as on the unlimed land for oats and wheat during the same period. On the unlimed land basic slag throughout most of the experiment has been appreciably superior to superphosphate in its residual effect on both clover and timothy. However, on the whole, it has been slightly less efficient than superphosphate on these crops on the limed land. Its superior showing on the unlimed land doubtless represents the benefit accruing from the lime carried, which, as previously noted, is equivalent to about 1480 pounds of calcium carbonate per ton. If all crops of the rotation for the entire period are considered, basic slag ranks about equal to superphosphate on the unlimed land and about three-fourths as efficient on the limed land.

Raw rock phosphate.—Among the experiments under consideration four furnish direct comparisons of rock phosphate and superphosphate. These include the Barnyard Manure Experiment, the Lime and Floats Experiment, the Phosphate Reaction Experiment, and the Greenhouse Pot Experiment.

In Table 24 are presented the efficiency ratings for rock phosphate in the Barnyard Manure Experiment as calculated from the increases for rock phosphate and superphosphate over both stall and yard manure. In this experiment the two phosphates have been applied in equal amounts, 320 pounds per rotation, which makes the application of phosphoric acid on the rock phosphate

TABLE 24.—Efficiency Ratings of Phosphoric Acid in Raw Rock Phosphate. Superphosphate = 100

Barnyard Manure Experiment

Crop	First 6-yr. period	Last 6-yr. period	Entire period*
Corn	31	8	24
Wheat	47	10	22
Clover	42	—9	17
Average	40	−1	19

*1897-1932 (Liming begun in 1905).

Note: Both rock phosphate and 16% superphosphate were used at the rate of 320 pounds per acre per rotation supplementing stall and yard manure applied at the rate of 8 tons for corn. Efficiency values were calculated separately for stall and yard manure plots and were then averaged to give the figures in the table.

plots practically double that on the superphosphate plots. The efficiency ratings shown in the table are efficiencies per pound of phosphoric acid and not per pound of total fertilizer applied.

In this experiment, before liming was begun, the efficiency of rock phosphate for all crops averaged 40 per cent. During the last 6 years of the experiment, after the soil had been brought to approximately pH 7.5 by repeated limng, rock phosphate showed an average efficiency of —1 per cent, clearly indicating a marked tendency for the availability of this phosphate to be seriously reduced at alkaline reactions. There appears to have been no great difference in the ability of the three crops to utilize the phosphorus of raw rock phosphate on the acid soil before liming was begun. During the last 6 years, the grain crops appear to make somewhat better use of phosphorus in this form than does red clover.

The Lime and Floats Experiment contains a direct comparison of 320 pounds of 16% superphosphate and an equal amount of rock phosphate applied to corn in a corn, oats, hay rotation on unlimed land. For the entire period, 1905-1932, the phosphoric acid of rock phosphate has shown an efficiency of 34.5 per cent for corn and 41.2 per cent for oats. The increases in the hay, which has been mixed clover and timothy with the latter predominating, have been too small from both phosphates to make the efficiency figure for the hay crop reliable.

In the Phosphate Reaction Experiment where rock phosphate and superphosphate are compared in amounts carrying 30 pounds of phosphoric acid (P_2O_5) per acre for wheat at three soil reactions, the results of a single wheat crop show efficiencies for rock phosphate of 6 per cent at pH 5.5, 3 per cent at pH 6.0, and 6 per cent at pH 7.0 calculated from the increases on wheat grain. The authors are unable to explain the unusually poor showing of rock phosphate at the more acid reactions in this experiment.

In the Greenhouse Pot Experiment rock phosphate and 20% superphosphate are compared at initial rates of 30, 60, and 90 pounds of P_2O_5 per acre, the results being measured in terms of phosphorus removed in six cuttings of Sudan grass. The average efficiency of rock phosphate in this experiment was 29 per cent in the pH 6 series and —39 per cent in the pH 7 series.

As a whole the evidence is interpreted as indicating an efficiency for rock phosphate of about 40 per cent for the common grain and hay crops considered in these experiments upon the unlimed Wooster and Canfield soils, the reaction being about pH 5 to pH 5.5. With liming its efficiency decreases to practically zero in the reaction range pH 7 to pH 7.5. That the same decrease in efficiency with increasing pH does not occur with such crops as sweet clover which, as is well known, possesses unusual capacity to feed upon rock phosphate and other insoluble minerals is indicated by the data from the Lime and Floats Experiment presented in Table 9. During the third 9-year period the hay seeded in this experiment was changed to sweet clover and alfalfa with the former greatly predominating in the crop as harvested. During this period, the increase produced by rock phosphate, potash, and quicklime was slightly larger than that produced by an equal amount of superphosphate with potash and quicklime, indicating an efficiency for the phosphoric acid in rock phosphate of at least 50 per cent for the sweet clover crop. The reaction of these soils during this period was approximately pH 7.0.

Ammonium phosphate.—Only the mono-ammonium phosphate has been included in these studies and it occurs only in the Phosphate Reaction Experiment[5]. The efficiency ratings for this material calculated from the increases in wheat grain are 69 per cent for the pH 5.5 series, 73 per cent for the pH 6.0 series, and 112 for the pH 7.0 series. While it is unsafe to draw conclusions from a single test, the data point to better utilization of this material at neutral than at acid reactions. In the same experiment, pure mono-calcium phosphate showed efficiencies of 86 at pH 5.5 and 81 at pH 6.0. It is possible that the poorer showing for the ammonium phosphate at these same reactions reflects in part its lack of calcium, although a deficiency of this element for wheat would scarcely be expected upon this soil, even at as acid a reaction as pH 5.5. A considerable number of experiments in other states indicate higher availability for the phosphoric acid of this material on soils of the northern states than was obtained on the two more acid ranges in this experiment.

Ammoniated superphosphates.—The process of ammoniating superphosphate, in which ammonia either in condensed liquid form or in water solution is used for treating ordinary superphosphates, has been extensively adopted by manufacturers of mixed fertilizers during the past 5 years. The effect of the process upon the efficiency of the phosphoric acid is thus of considerable practical importance to users of mixed fertilizers. Two grades of ammoniated superphosphate containing, respectively, 2.49 and 5.01 per cent nitrogen were compared with 20% superphosphate at three soil reactions in the Phosphate Reaction Experiment. In the Greenhouse Pot Experiment three grades of ammoniated superphosphate containing, respectively, 2.90, 5.36, and 7.12 per cent nitrogen were compared with superphosphate (19.45 per cent available P_2O_5) at three rates of application (viz., 30, 60, and 90 pounds of phosphoric acid per acre) and at two reactions, approximately pH 6 and pH 7. The efficiencies for the phosphoric acid of the ammoniated superphosphates obtained in both experiments are shown in Table 25. The values given for the pot experiment are averages for all three rates of application.

The efficiencies shown lack sufficient consistency to warrant definite conclusions. Particularly, the values for pH 6.0 in the Phosphate Reaction Experiment appear abnormally low compared to those for the other reactions in the same experiment and to those for the corresponding reaction in the other experiment. However, the following indications may be noted: There is a tendency for the availability to decrease with increasing nitrogen content

[5]Mono-ammonium phosphate is sold under the trade name of "Ammo-Phos A". This product carries 11 per cent nitrogen and 48 per cent available phosphoric acid. It is being found well adapted as a top- and side-dresser on pastures, hay, truck, and orchard crops and as an ingredient in concentrated mixed goods, both commercial and home mixed.

TABLE 25.—Efficiency Ratings of Phosphoric Acid in Ammoniated Superphosphate. Superphosphate = 100

Phosphate Reaction and Greenhouse Pot Experiments

Soil reaction (approx.) pH	Ammoniated superphosphate Grade 1		Ammoniated superphosphate Grade 2		Ammoniated superphosphate Grade 3	
	Nitrogen content	Efficiency	Nitrogen content	Efficiency	Nitrogen content	Efficiency
	Pct.	Pct.	Pct.	Pct.	Pct.	Pct.
Phosphate Reaction Experiment*						
5.5	2.49	94	5.01	72	....	....
6.0	2.49	74	5.01	48	....	....
7.0	2.49	100	5.01	59	....	....
Greenhouse Pot Experiment†						
6.0	2.90	87	5.36	86	7.12	77
7.0	2.90	72	5.36	50	7.12	23

*Efficiencies are calculated from increases in wheat grain.

†Efficiencies are calculated from P_2O_5 removals by six cuttings of Sudan grass and are averages for three rates of application of phosphoric acid.

at all reactions. The efficiency of the two low nitrogen materials is relatively high, ranging from 72 to 100 per cent, and is not markedly affected by variation in soil reaction. The efficiency of the two materials listed under "Grade 2" and containing approximately 5 per cent nitrogen decreases with increasing pH, being approximately one-half as efficient as superphosphate at pH 7. The most highly ammoniated material, 7.12 per cent nitrogen, used only in the pot experiment, drops markedly in efficiency in passing from pH 6 to pH 7, its efficiency at the latter reaction being approximately one-fourth that of superphosphate. From data of Keenan (11), who has investigated the reactions occurring in the superphosphate ammoniation process, the phosphoric acid in the Grade 1 materials probably occurs in about equal proportions as mono-ammonium and di-calcium phosphates, that in the Grade 2 materials about one-fourth as mono-ammonium and three-fourths as tri-calcium phosphate, and that in the Grade 3 material practically all as tri-calcium phosphate. In both experiments the efficiency of tri-calcium phosphate is notably low at pH 7, its rating being 23 per cent in the Phosphate Reaction Experiment and 35 per cent in the Greenhouse Pot Experiment. The falling off in efficiency of Grades 2 and 3 at pH 7 is in agreement with what might be expected from their tri-calcium phosphate contents. These results are in substantial agreement with those of Ross, Jacob, and Beeson (16) who have reported the results of a series of collaborative greenhouse studies of the efficiency of a large number of phosphatic materials including several ammoniated superphosphates varying widely in nitrogen content. The experiments were divided into two groups, one with soils below pH 6 and the other above pH 6. The latter group gave, as a whole, much lower efficiency values for the highly ammoniated superphosphates than the acid soil group; whereas the efficiencies for the ammoniated superphosphates of low nitrogen content did not differ widely in the two groups. It should be pointed out that in commercial ammoniation practice, it is seldom that more than 2 per cent of nitrogen is introduced. Accordingly, the decreased efficiency of the higher nitrogen materials at high pH is of more theoretical than practical interest.

SUMMARY AND CONCLUSIONS

This bulletin deals with the effects that liming the naturally acid Wooster and Canfield silt loams has upon the availability of soil phosphorus and upon the comparative efficiency of different phosphate fertilizers.

Data are presented from four long-time and two short-time field experiments and from one greenhouse study. The older experiments afford an opportunity of studying changes in the relative efficiencies of superphosphate, bone meal, basic slag, and rock phosphate over a period of years, both on unlimed soil and on soil whose reaction has been made progressively more alkaline by repeated liming. One short-time field experiment deals with the response of several crops to superphosphate on soil maintained at five different pH levels. The efficiencies of some of the newer phosphate fertilizers including ammonium phosphate and ammoniated superphosphate containing different amounts of nitrogen are compared with those of superphosphate and rock phosphate in a one-year field experiment and in the Greenhouse Pot Experiment. In the field experiments yield increases are employed as the criterion of phosphate availability. In the greenhouse study phosphorus removal by six cuttings of Sudan grass is the criterion used.

In the older experiments there occurred a notable tendency for phosphate response to decline as the soil reaction was changed from about pH 5 to about pH 7.5 by repeated lime applications. In these same experiments the yields of plots receiving either nitrogen and potash or manure but no phosphorus remained about constant or increased on limed land but decreased markedly on unlimed land. These facts are interpreted as indicating an increase in the availability of native soil phosphorus as the reaction is made more alkaline up to about pH 7.5.

The foregoing interpretation is supported by data from the short-time Legume-Reaction Experiment in which the response of a number of crops to superphosphate at five pH levels, approximately 4.5, 5.0, 6.0, 7.0, and 7.5, decreased in both directions from about pH 5 or pH 6. With most crops very nearly maximum yields were produced at the most alkaline reaction without phosphate. Soil phosphorus soluble in dilute organic acids at constant pH also was lowest at pH 5, increased markedly up to pH 7.5, and was higher at pH 4.5 than at pH 5. Agreeing with these observations, Sudan grass in the Greenhouse Pot Experiment removed considerably more phosphorus from unphosphated soil at pH 7 than at pH 6.

In terms of practice, these facts indicate that by maintaining the reaction of these soils at about pH 7.5 satisfactory yields of crops may be produced with the minimum investment in phosphate fertilizers.

The comparatively low response to superphosphate at alkaline reactions may have been due not alone to the greater availability of soil phosphorus but also to a greater fixation of the applied phosphate. The experiments did not permit a satisfactory evaluation of the latter factor but data from the greenhouse experiment afford some evidence that it was operative.

Steamed bone meal showed an efficiency compared to superphosphate of about 80 per cent for the cereals and timothy and was about equal to superphosphate for clover on unlimed land, approximately pH 5. As the soil reaction was increased to about pH 7.5 by repeated liming, the efficiency of the bone decreased to zero for corn, to about 20 per cent for oats and wheat, and to 30 per cent for clover. It is concluded that bone meal is an unsatisfactory source of phosphoric acid on limed Wooster and Canfield soils.

Basic slag phosphate showed an efficiency compared to superphosphate of about 85 per cent for the cereals on unlimed land and was about 40 per cent superior to superphosphate for clover under the same conditions. With repeated liming to about pH 7.5, the efficiency of basic slag dropped to zero for corn but only to about 70 per cent for wheat and oats and to 85 per cent for clover.

The phosphorus of rock phosphate had an efficiency of around 40 per cent for both grain crops and clover on unlimed land. With repeated liming to about pH 7.5 its efficiency dropped to 10 per cent or less for the same crops. Its efficiency for sweet clover at about pH 7 was a little above 50 per cent.

Mono-ammonium phosphate, in a one-year field experiment with wheat, showed an efficiency, compared to superphosphate, of 69 per cent at pH 5.5. This increased to 73 per cent at pH 6 and to 112 per cent at pH 7. Although pointing to better utilization of this material on neutral than on acid soils, the data are too meagre to be considered conclusive.

The efficiency of the ammoniated superphosphate, measured in a one-year field experiment with wheat and in the greenhouse experiment with Sudan grass, varied with both the degree of ammoniation (nitrogen content) and the soil reaction. The materials containing less than 3 per cent nitrogen showed efficiencies ranging from 72 to 100 per cent with no consistent variations in efficiency between soil reactions of pH 5.5 to pH 7. The material containing about 5 per cent nitrogen showed lower availability than the less highly ammoniated product at all reactions. The material containing about 7 per cent nitrogen was still less efficient. Both the 5 and 7 per cent materials decreased in efficiency with increasing pH, the latter more markedly, its average efficiency in the greenhouse experiment being only 23 per cent at pH 7.

In general, it appears that the efficiency of all phosphate fertilizers on these soils decreases as the soil reaction approaches alkalinity. Compared to superphosphate, the efficiency of the more acid phosphates, mono-ammonium and mono-calcium phosphates, tends to increase with increasing pH, that of low-ammoniated superphosphate changes very little whereas materials containing phosphorus in the form of tri-calcium phosphate, either as such (highly ammoniated superphosphates) or in carbonate or fluoride combinations (bone meal and rock phosphate, respectively) show decreasing efficiency with increasing pH and are not well adapted for use on neutral or alkaline soils. Basic slag appears to occupy an intermediate position between these two groups of phosphates.

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